Application of imaging ellipsometry: graphene - pinpointing and ellipsometric characterization

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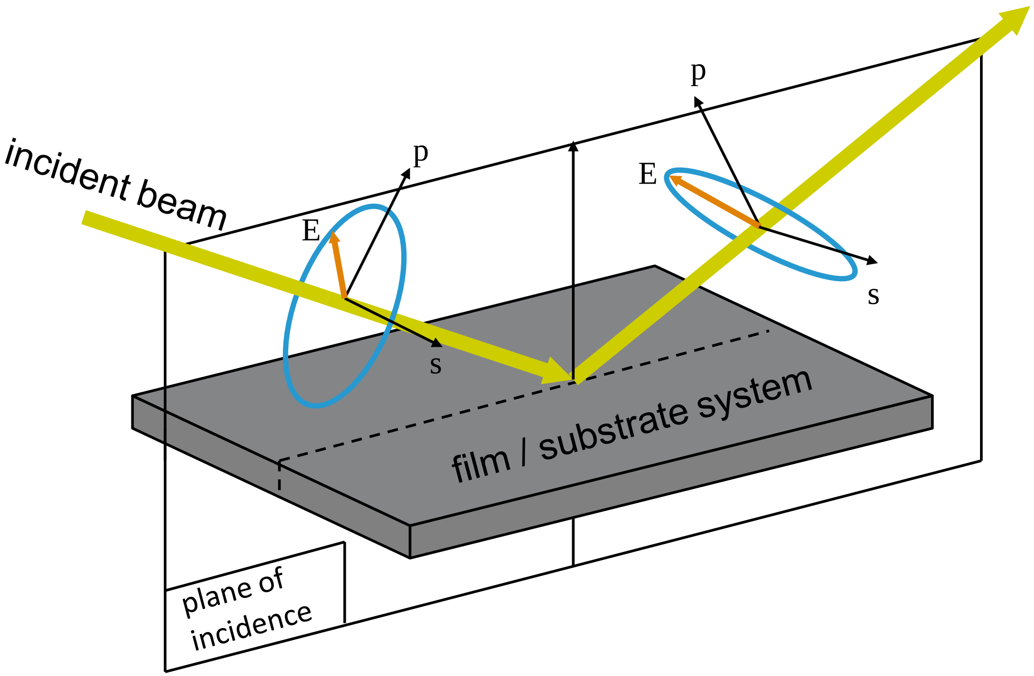
PETER H. THIESEN

- Introduction to imaging ellipsometry

Ellipsometry in general makes use of the fact that the polarization state of light may change when the light beam is reflected from a surface.



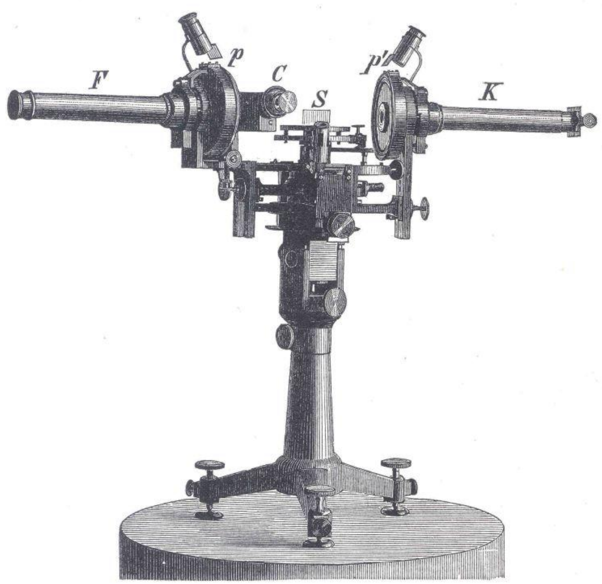
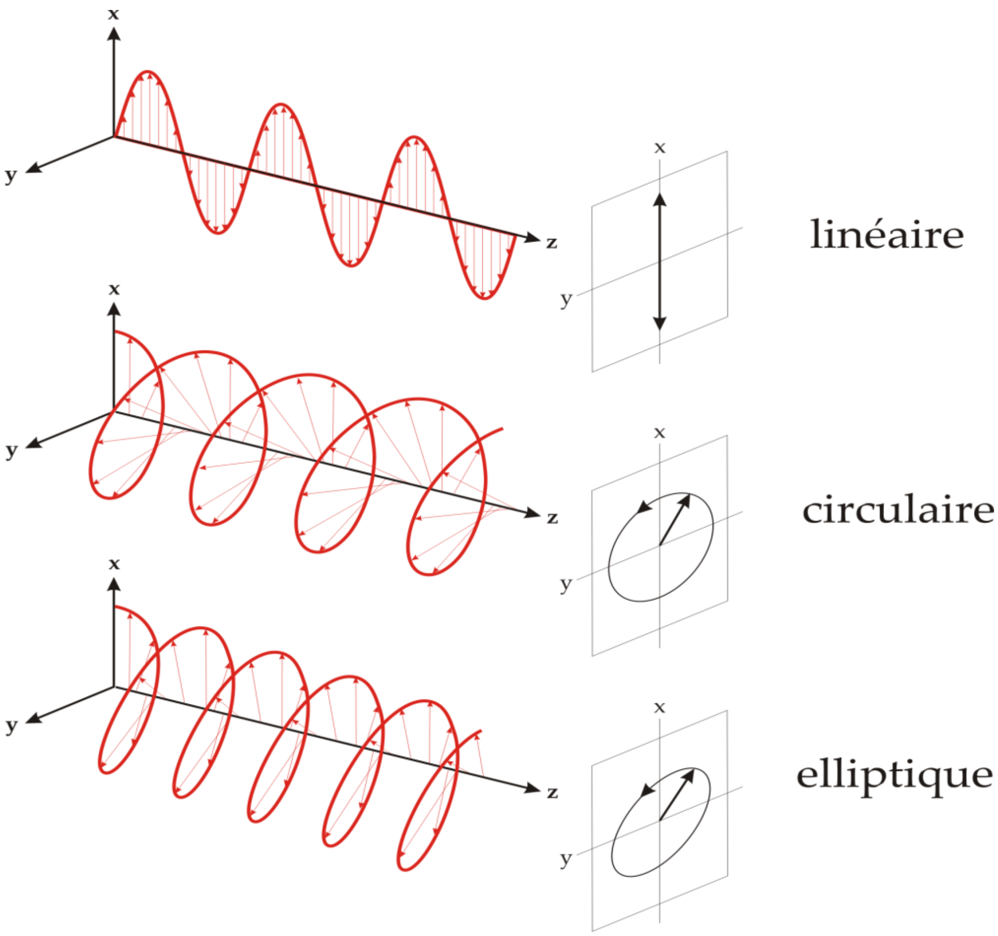


Fig. 81.

(Paul Drude, *Lehrbuch der Optik*, Leipzig, 1906)



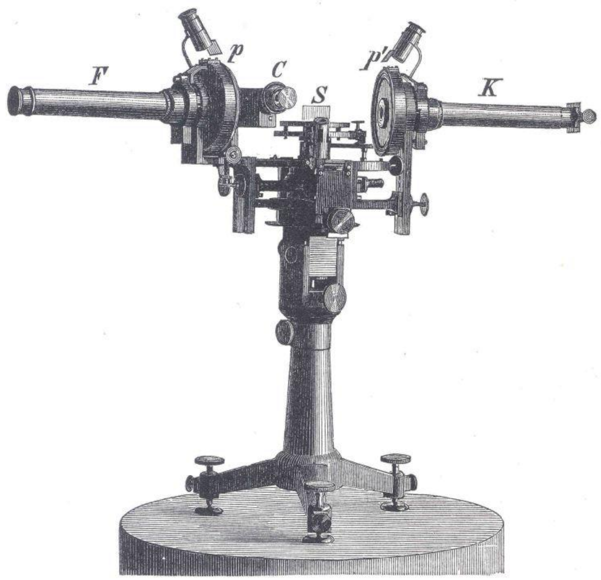
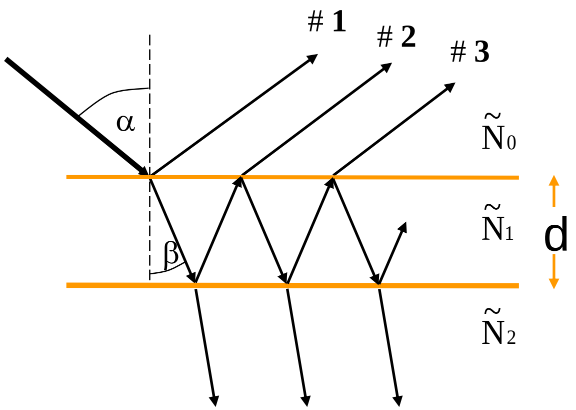


Fig. 81.

(Paul Drude, *Lehrbuch der Optik*, Leipzig, 1906)

Reflections at optical interfaces &

coherent superposition of the partial beams



Change of amplitudes and phases of the p- and s-polarised components of the reflected beam:

$$\rho = \tan\Psi \; e^{i\Delta} = \frac{R^p}{R^s} = \left\{ \frac{\left(\frac{\text{E } reflected \; (p)}{\text{E } incident \; (p)} \right)}{\left(\frac{\text{E } reflected \; (s)}{\text{E } incident \; (s)} \right)} \right\}$$

$$\Delta \equiv \delta_{pp} - \delta_{ss}$$

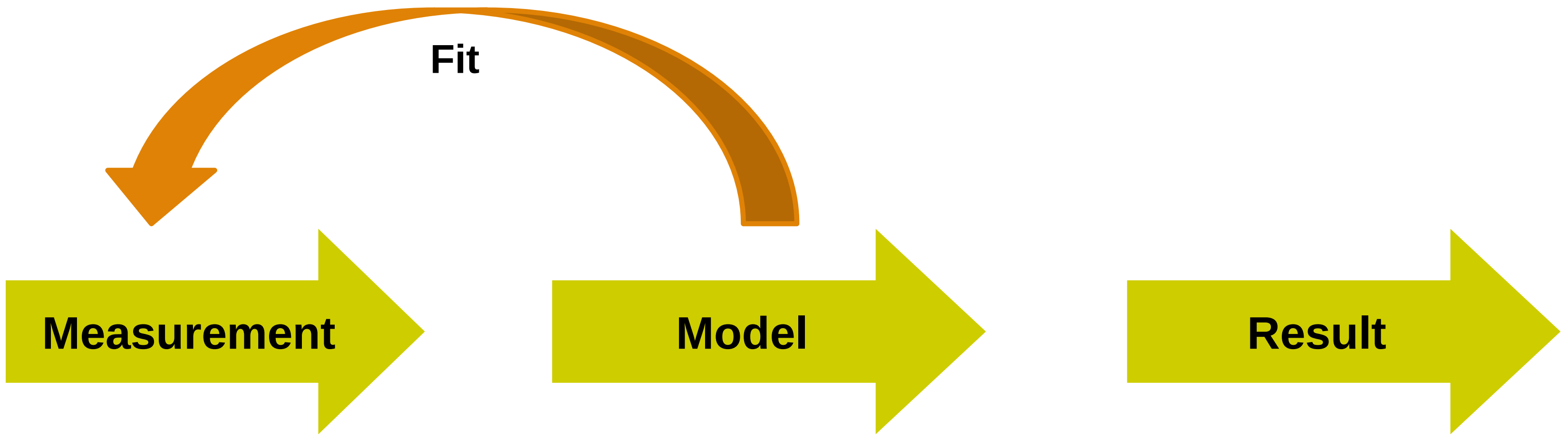
$$\delta_{pp} = \delta^{p}\text{out} - \delta^{p}\text{in}$$

$$\delta_{ss} = \delta^{s}\text{out} - \delta^{s}\text{in}$$

$$\tan\Psi \equiv \frac{|R^p|}{|R^s|}$$

Measurement precision for d: ca. 0.01nm !

„Ellipsometry is a method based on models“



- Measurands Δ, ψ

- Layer thickness d
- Optical properties n, k

(for all layers + substrate)

- Searched variables d, n, k,…

How does it work ?

nanofilm_ep3se , 2009

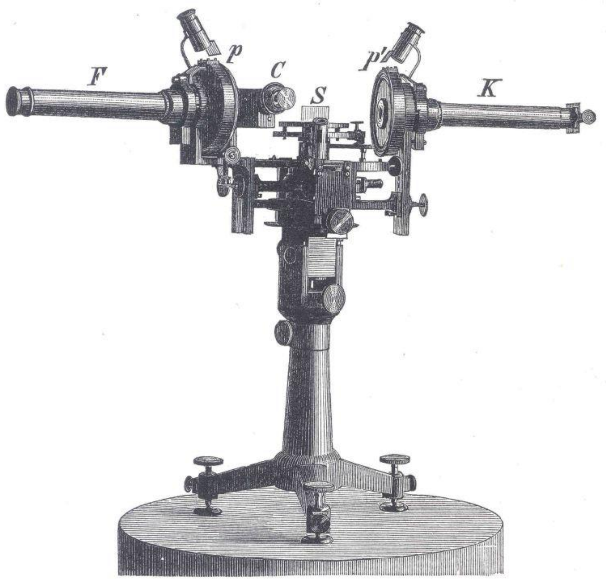
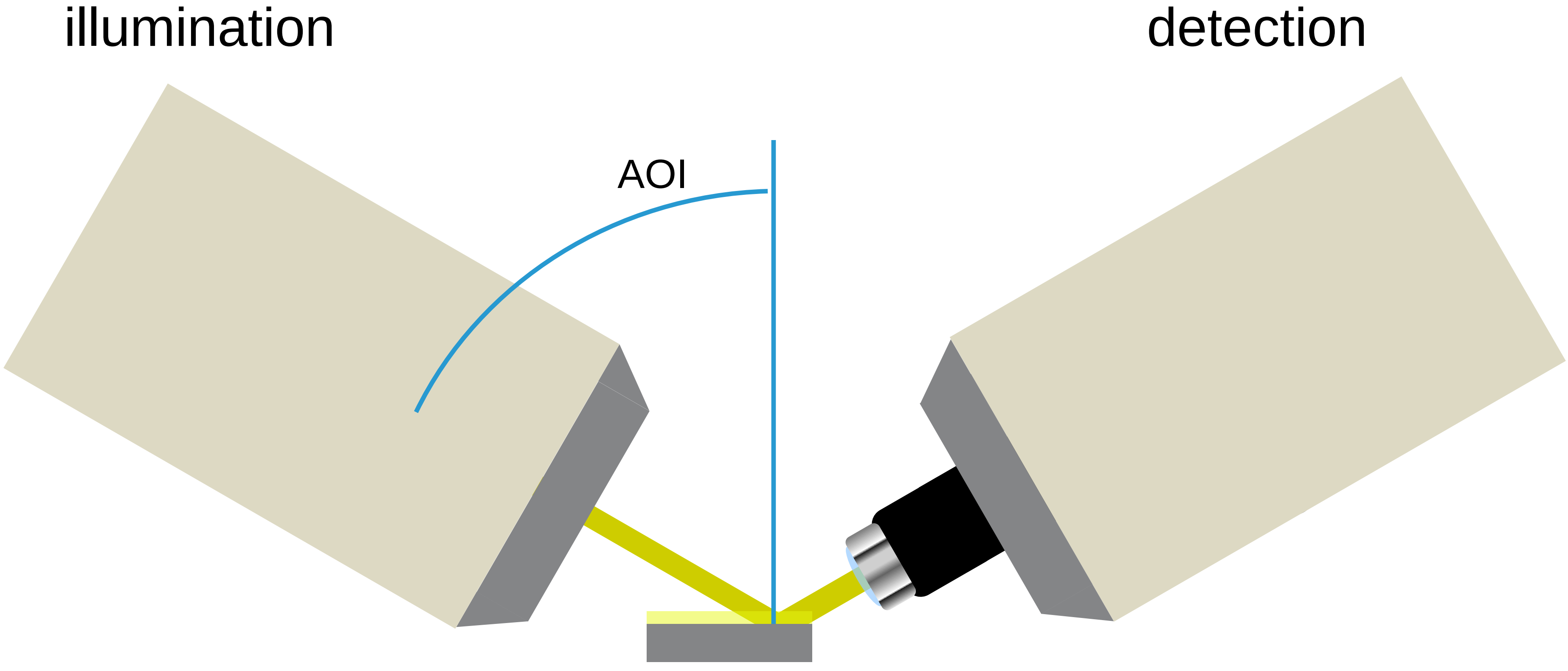
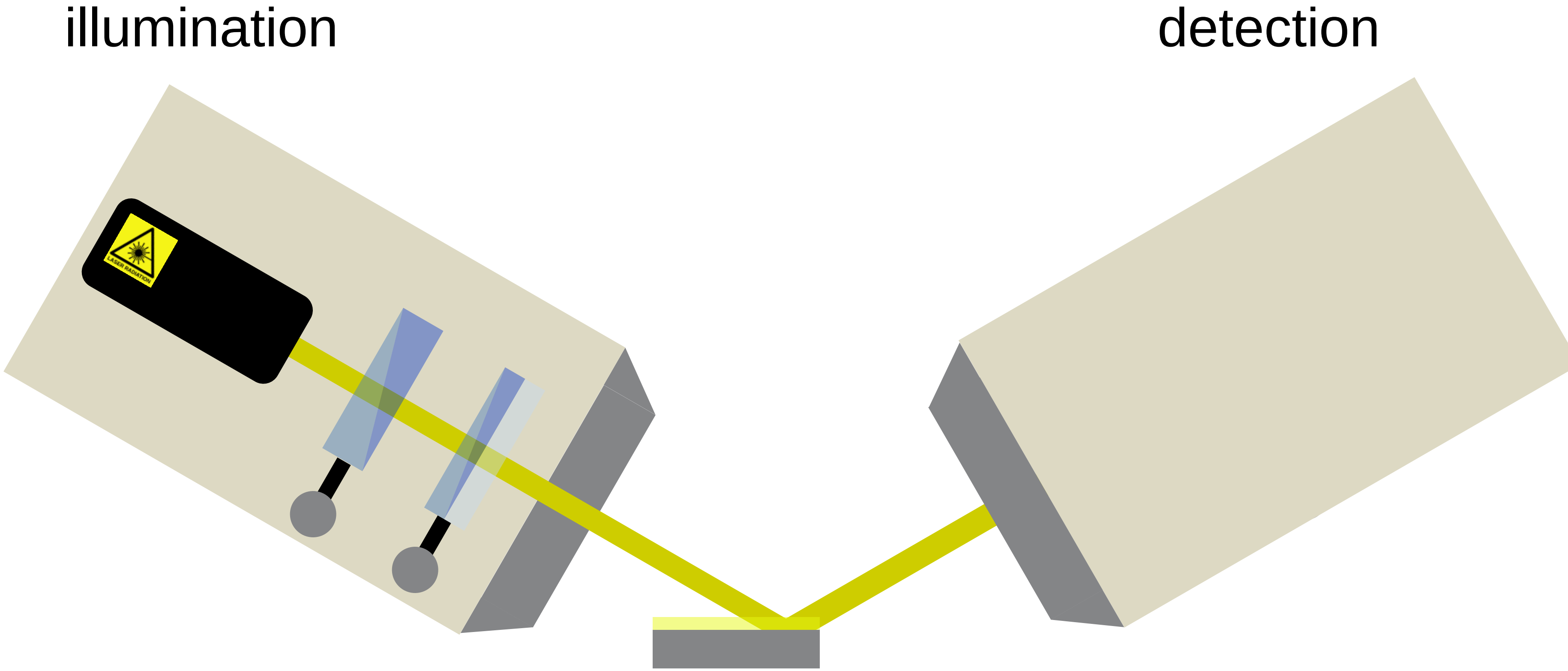


Fig. 81.

(Paul Drude, *Lehrbuch der Optik*, Leipzig, 1906)

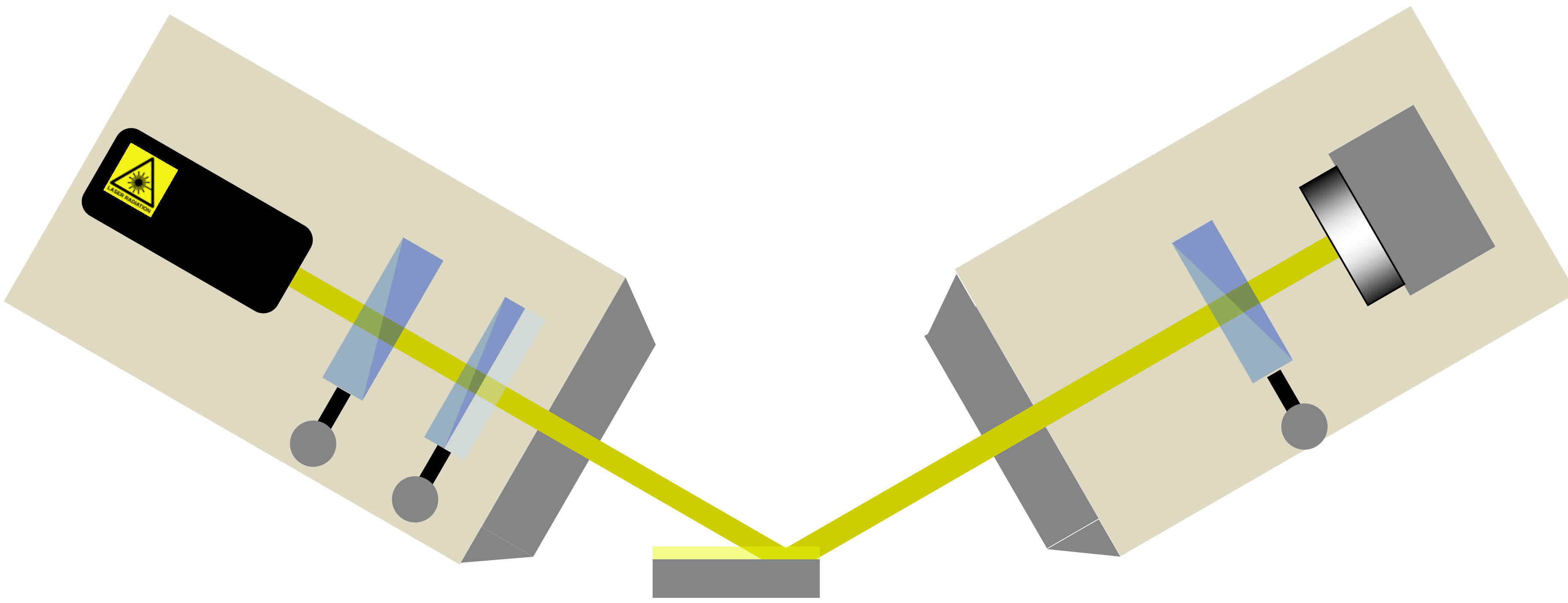

illumination
detection
AOI

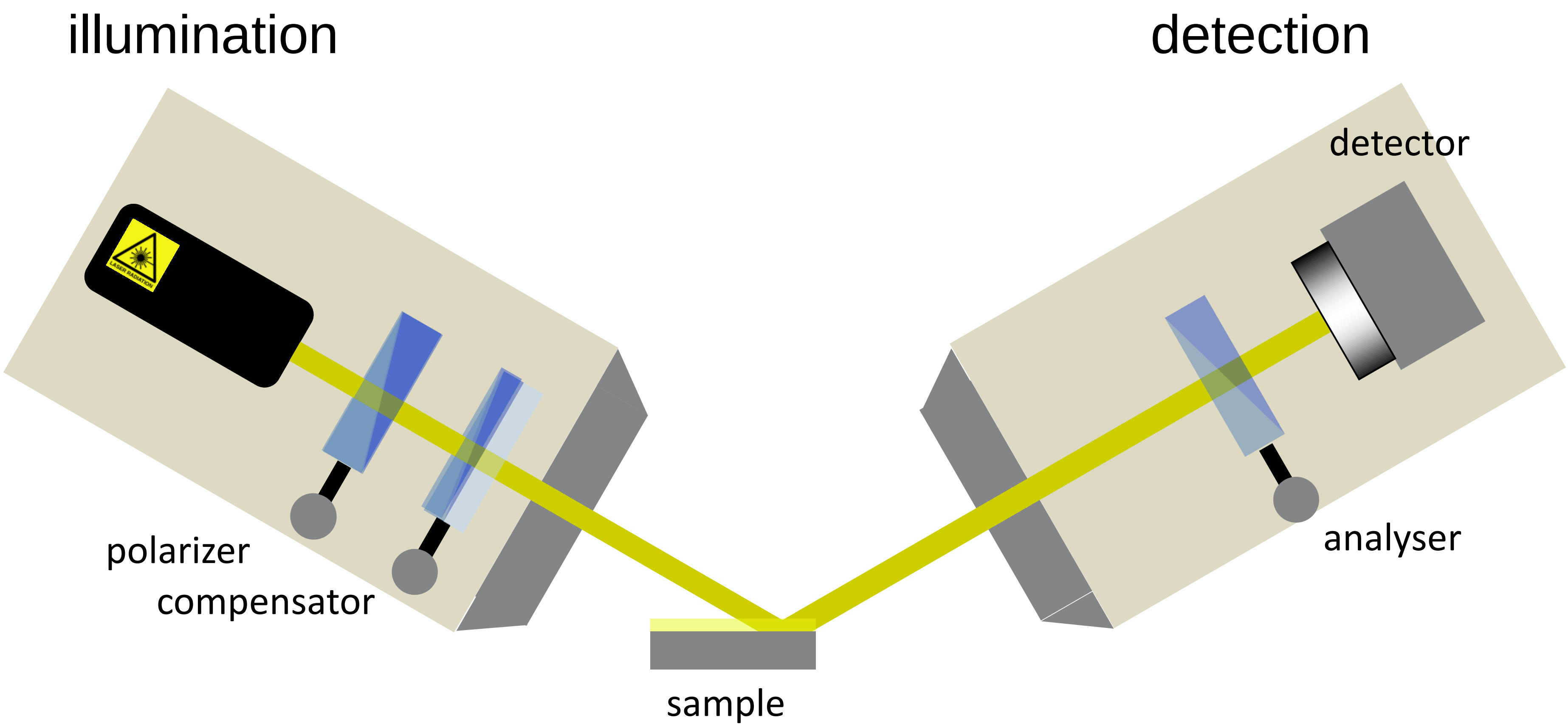
accurion

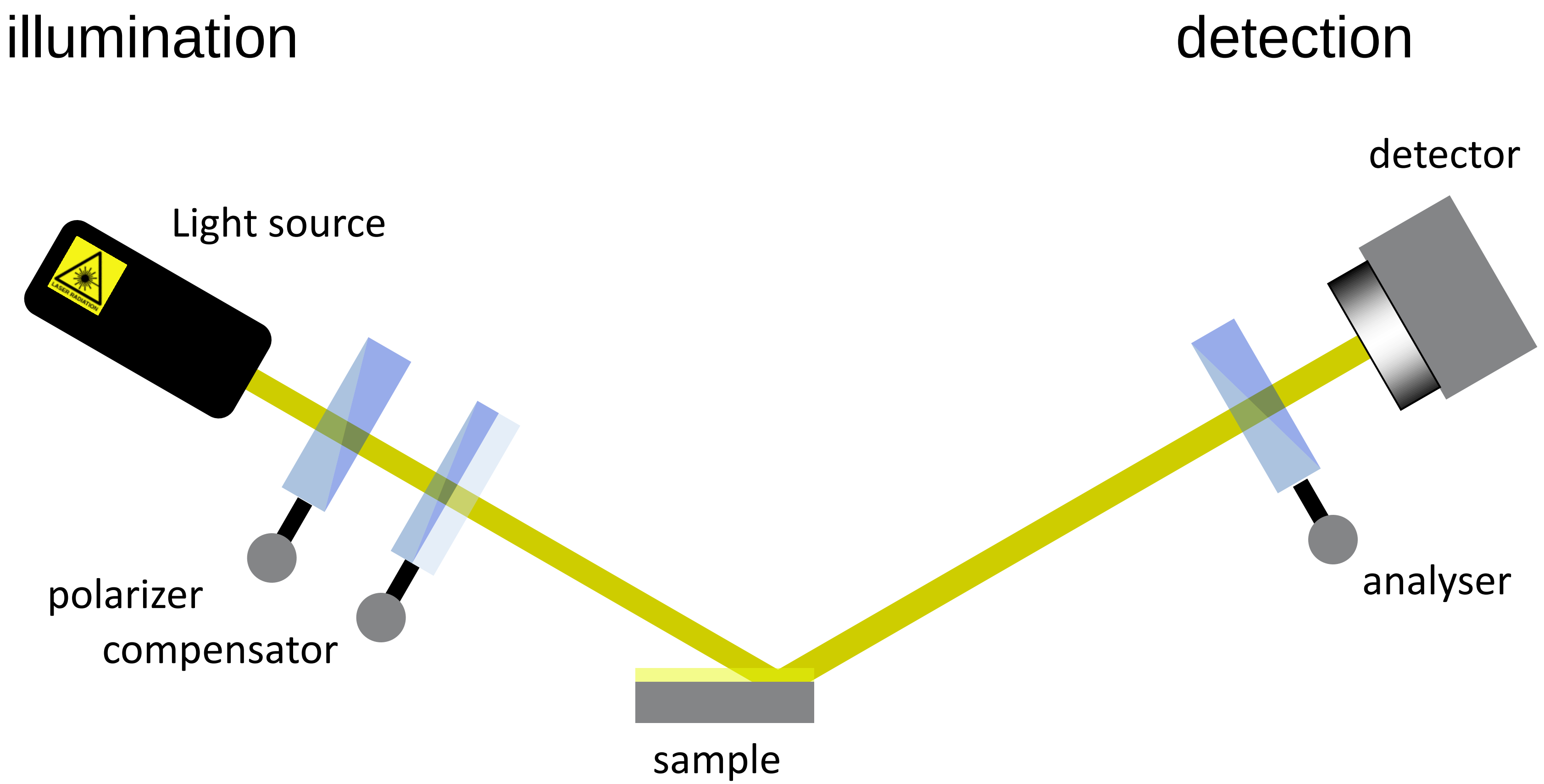


illumination

detection

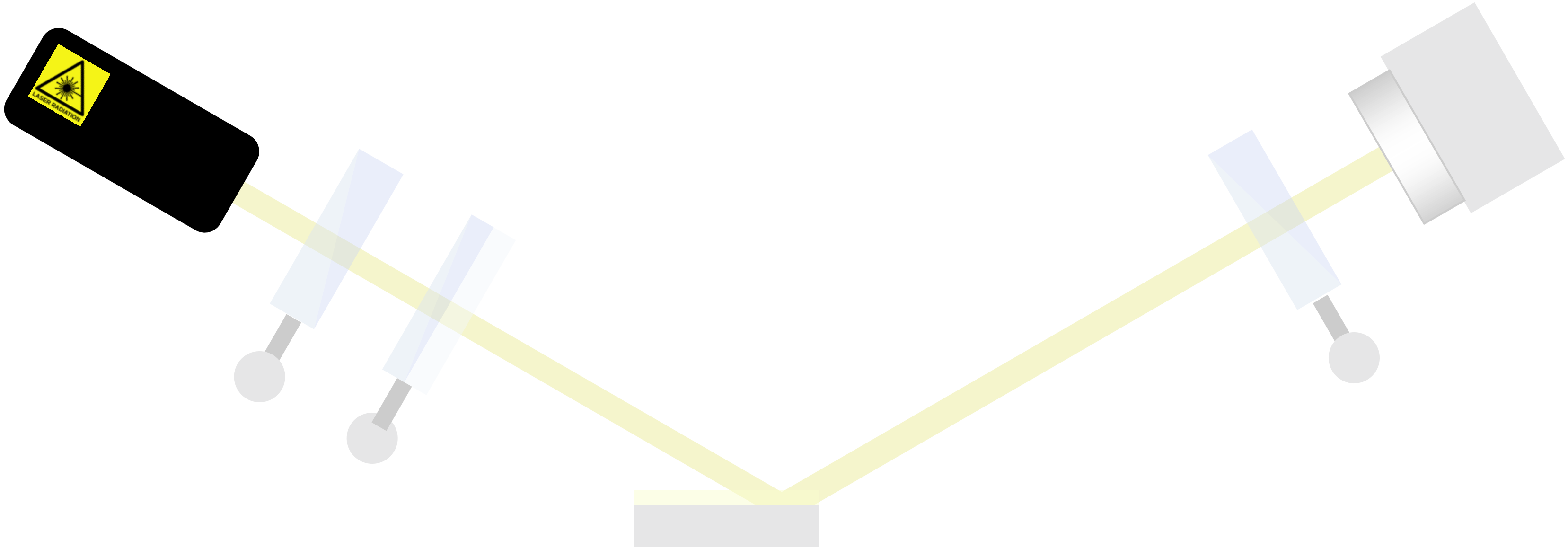


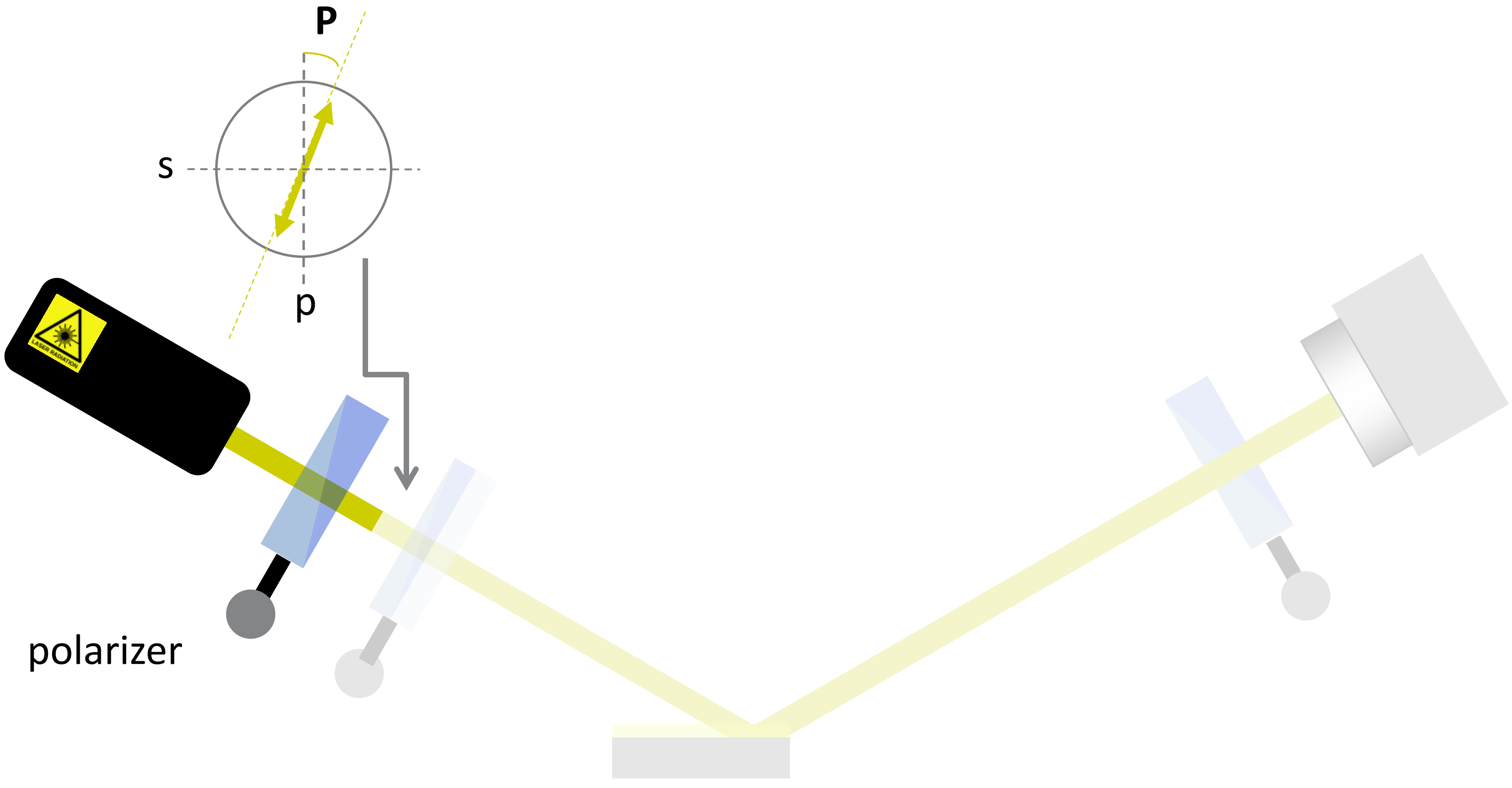

illumination
detection
detector
polarizer
compensator
analyser
sample

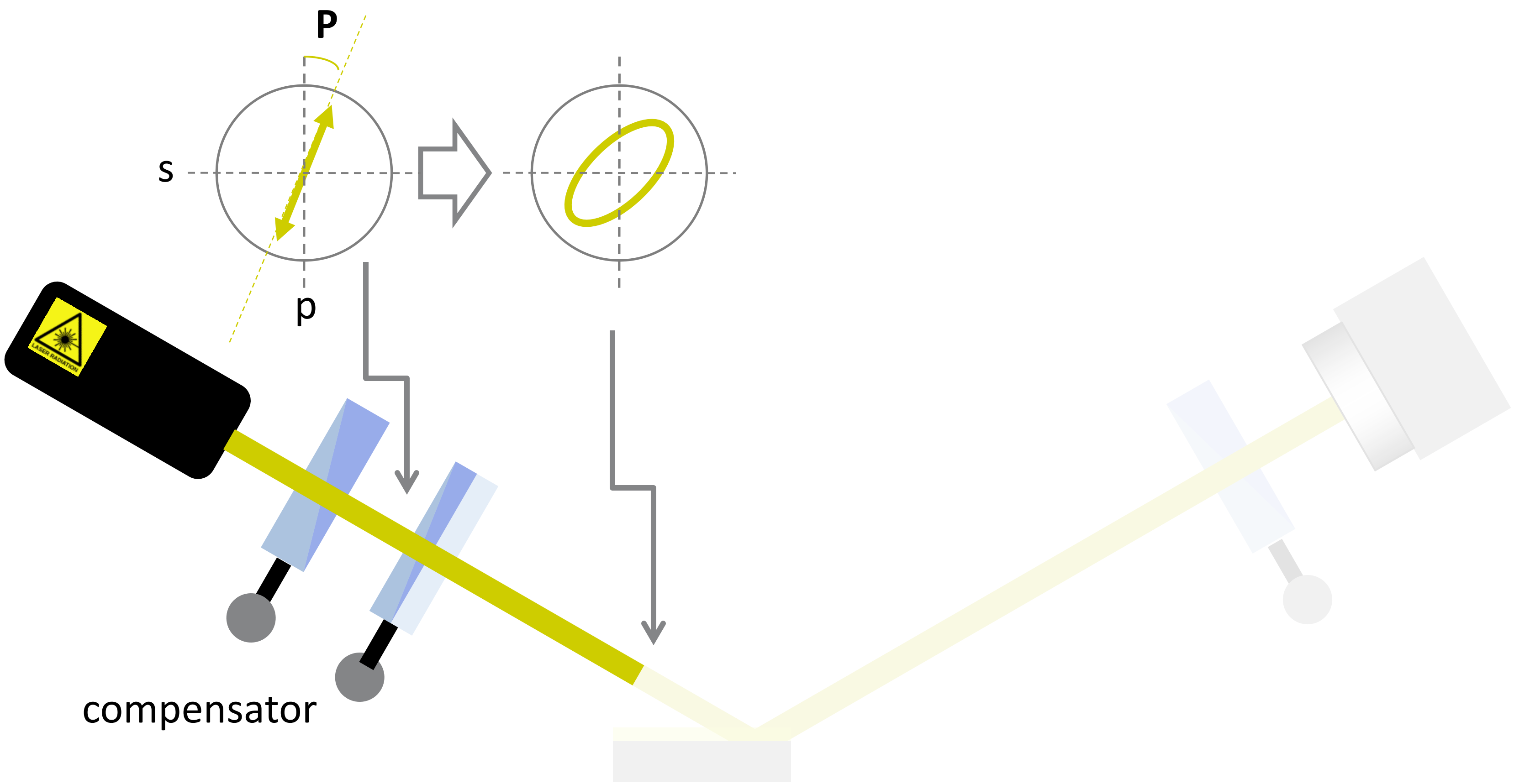

illumination
detection
Light source
detector
polarizer
compensator
sample
analyser

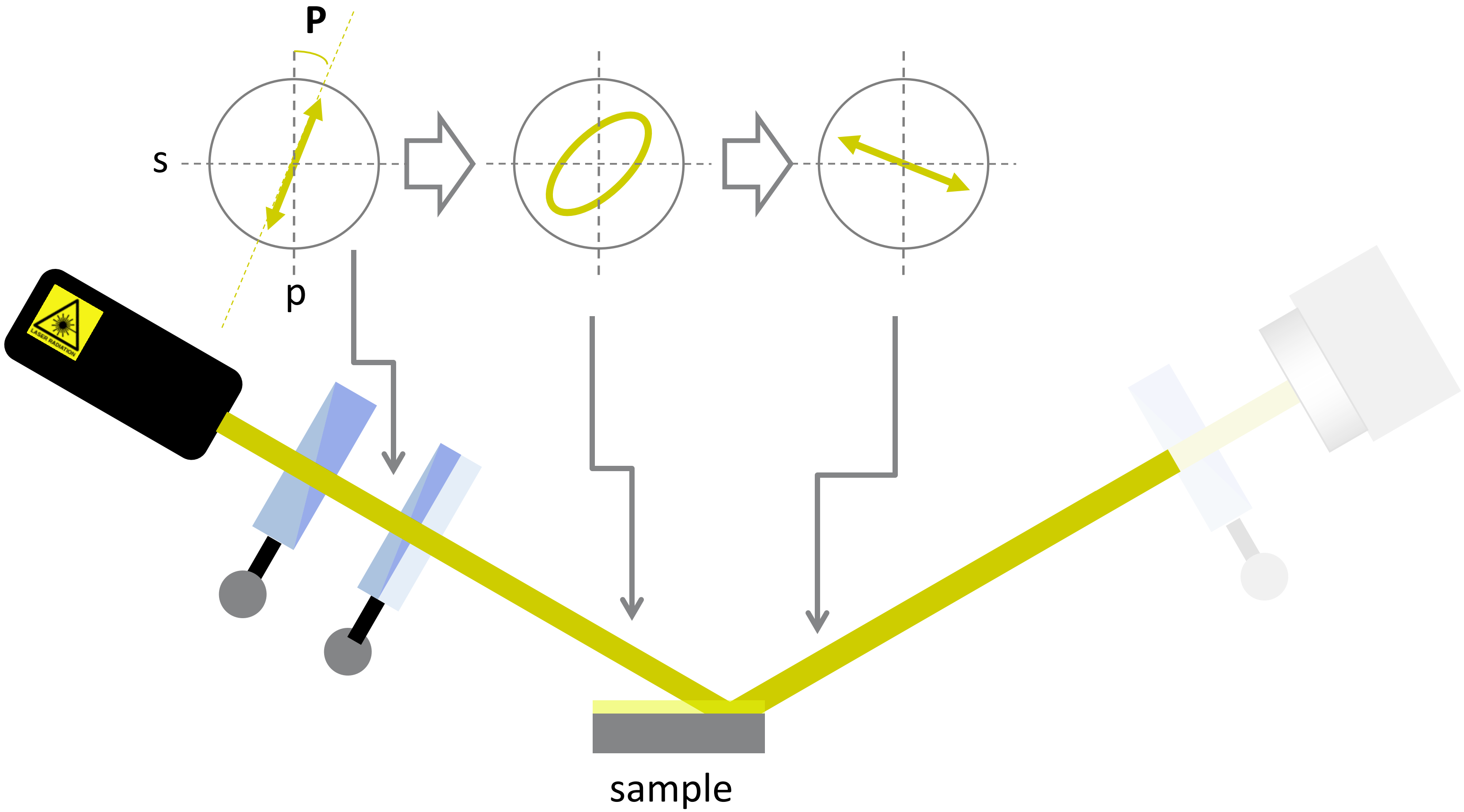
accurion

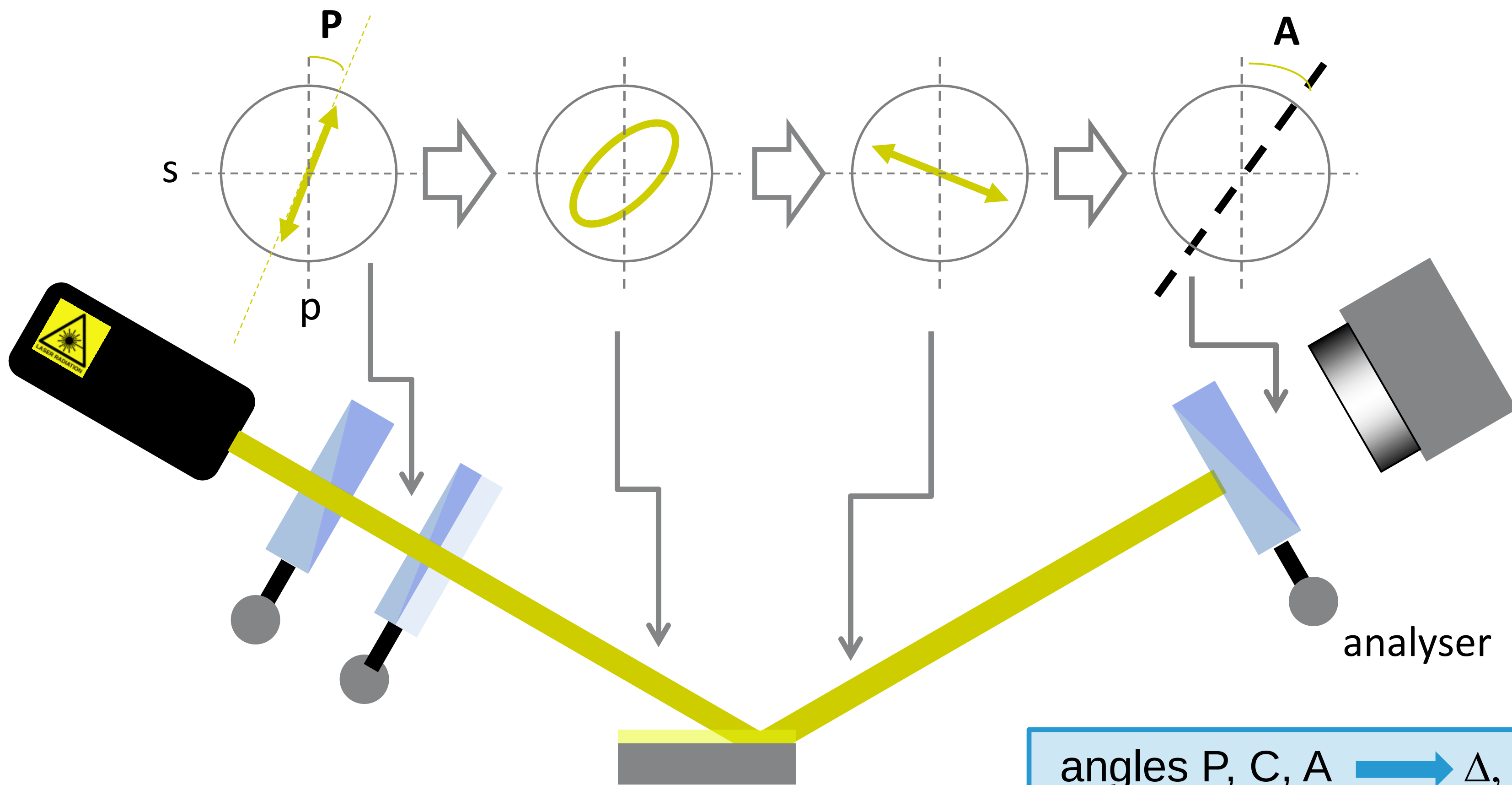
Method: *Nulling* Ellipsometry




P
s
p
polarizer


P
s
p
compensator


P
s
p
LASER RADIATION
sample



angles P, C, A $\rightarrow$ Δ, Ψ

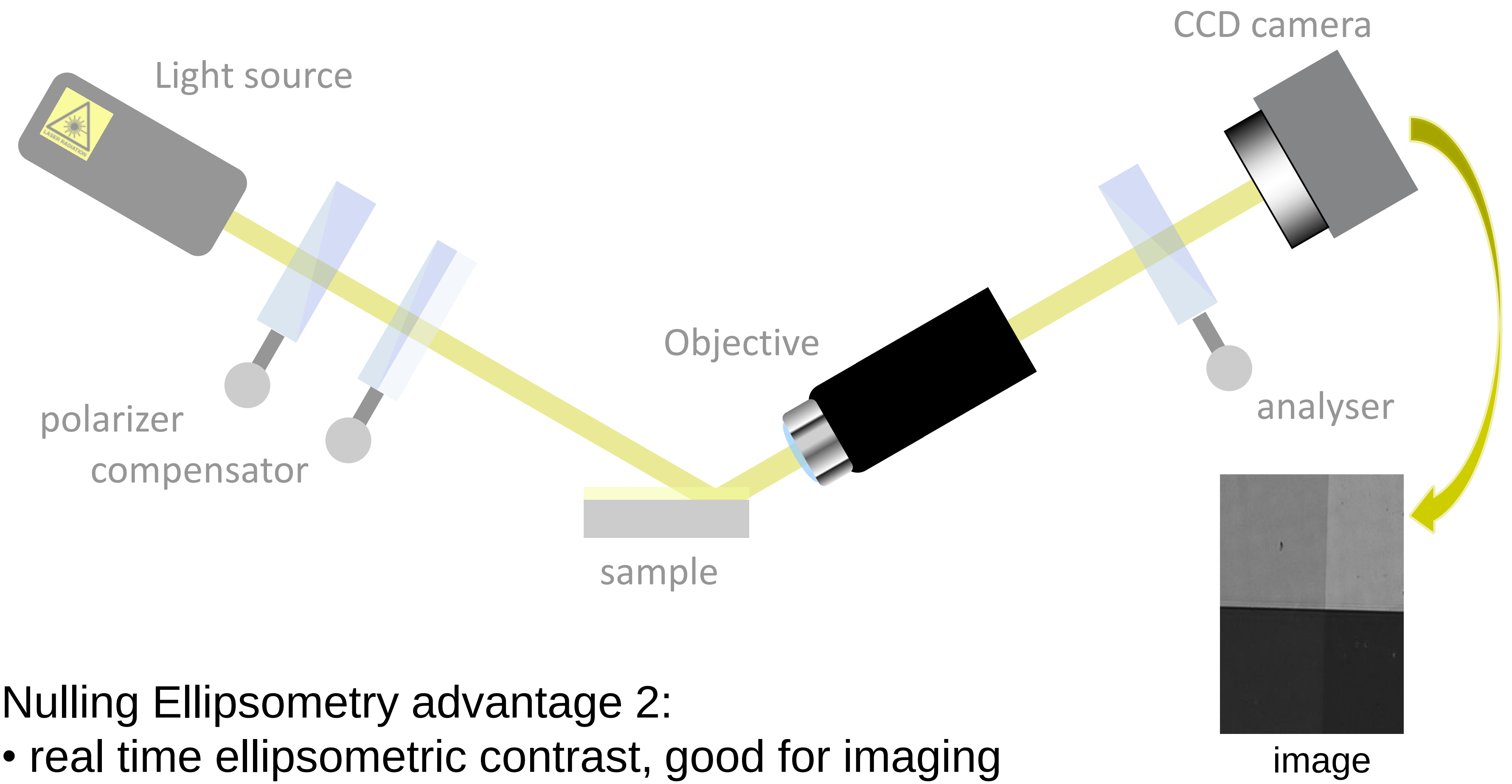
ideal instrument, C=45°:

$$\Delta = -2P \mp 90^\circ \quad \Psi = \pm A$$

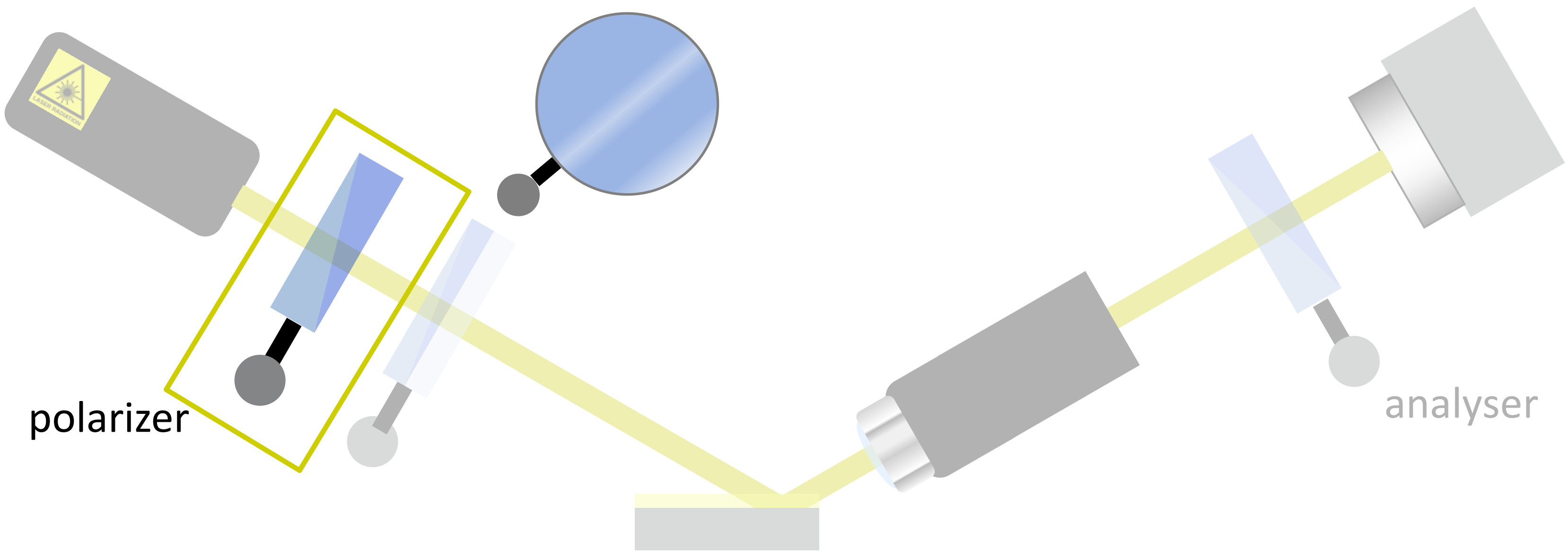
Nulling Ellipsometry advantage 1:

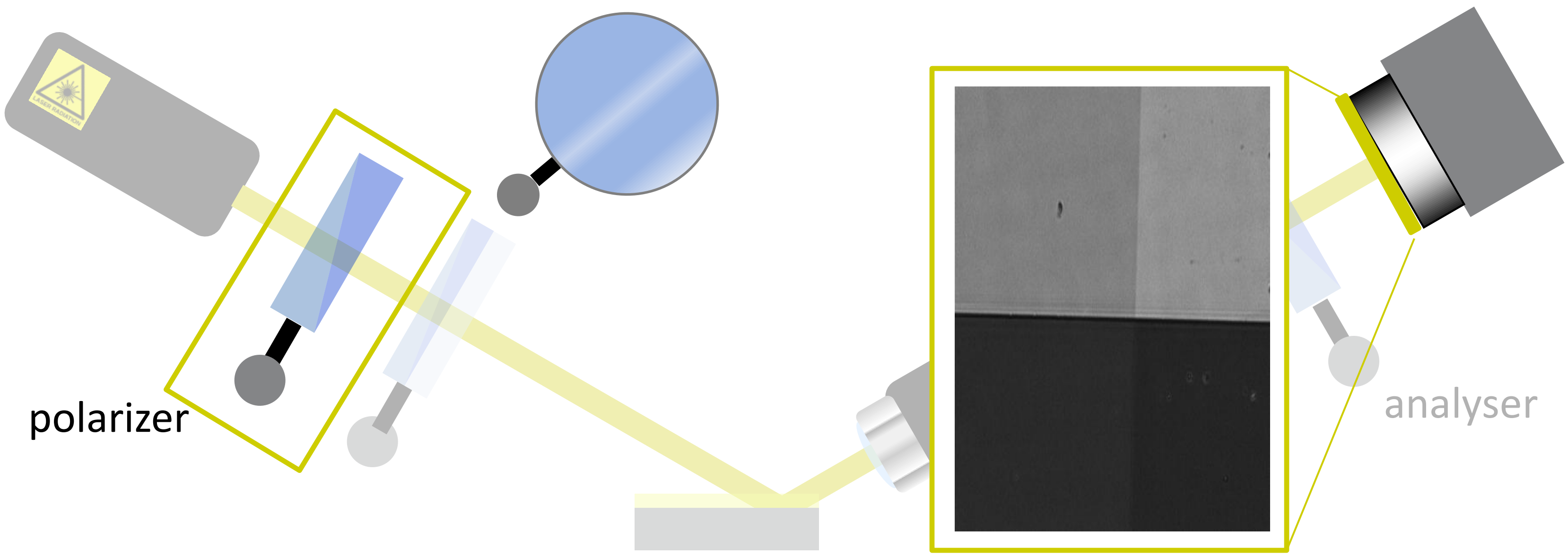
- high sensitivity for ultra-thin films

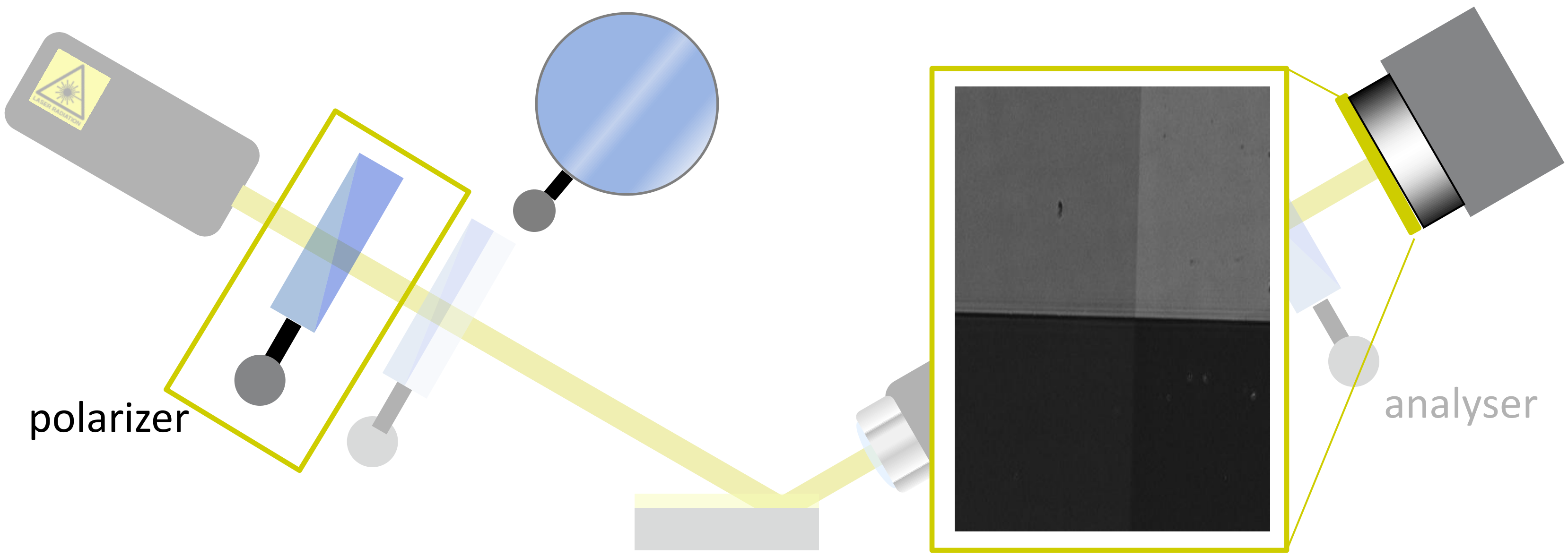
Nulling Ellipsometry ➡ Imaging Ellipsometry

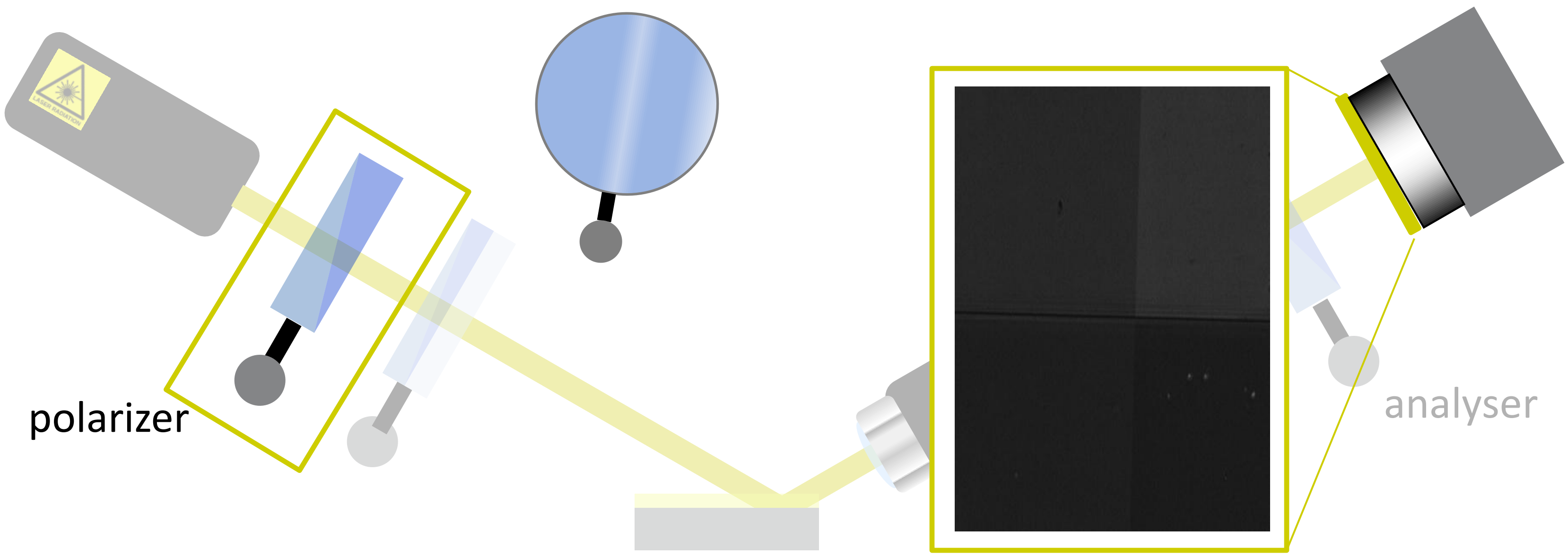


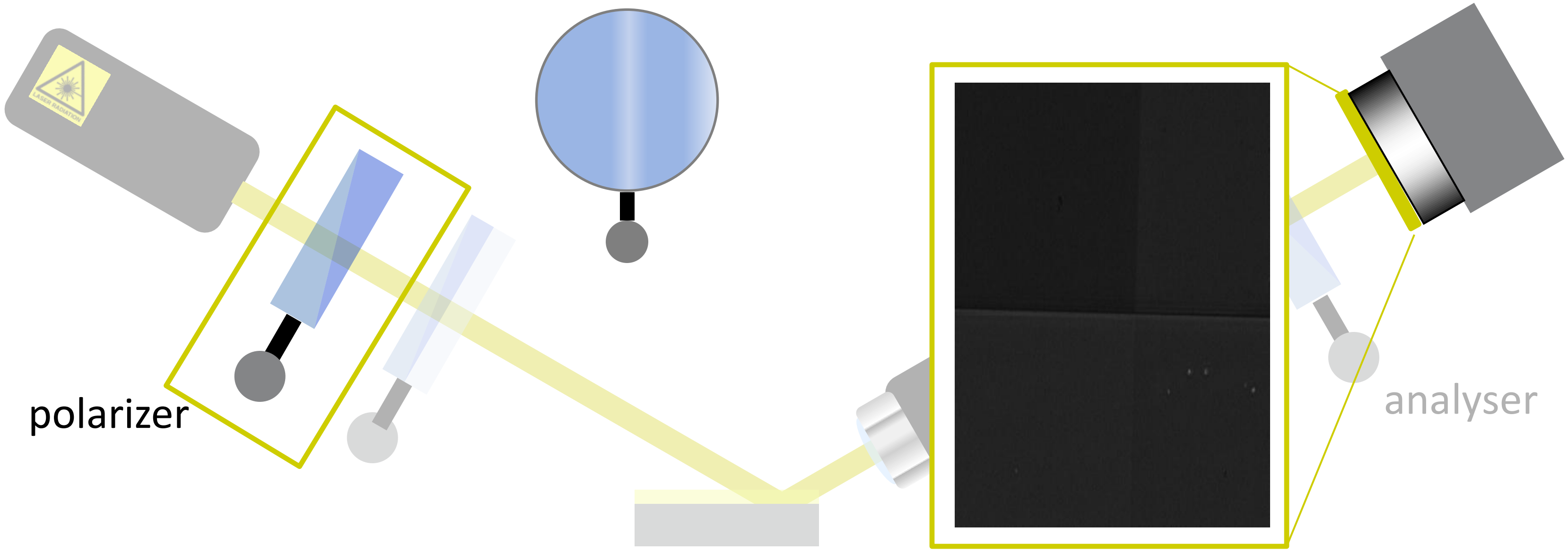
Nulling Ellipsometry advantage 2:
• real time ellipsometric contrast, good for imaging

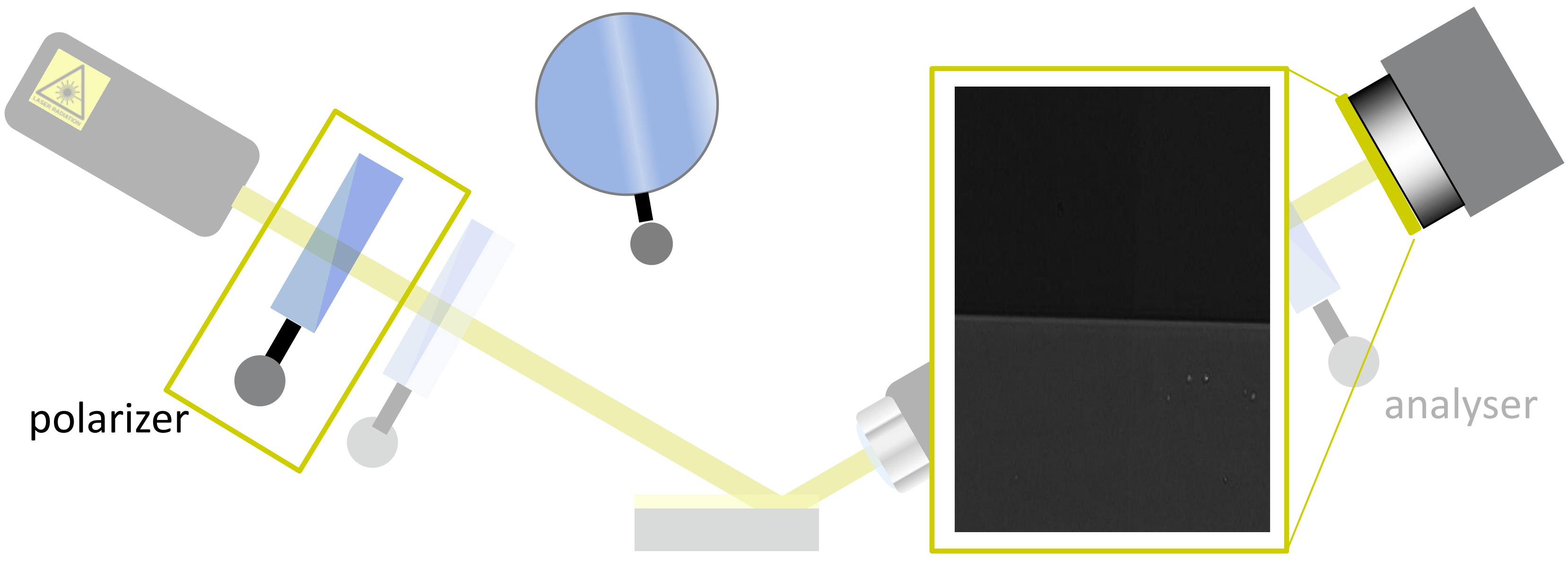

polarizer
analyser

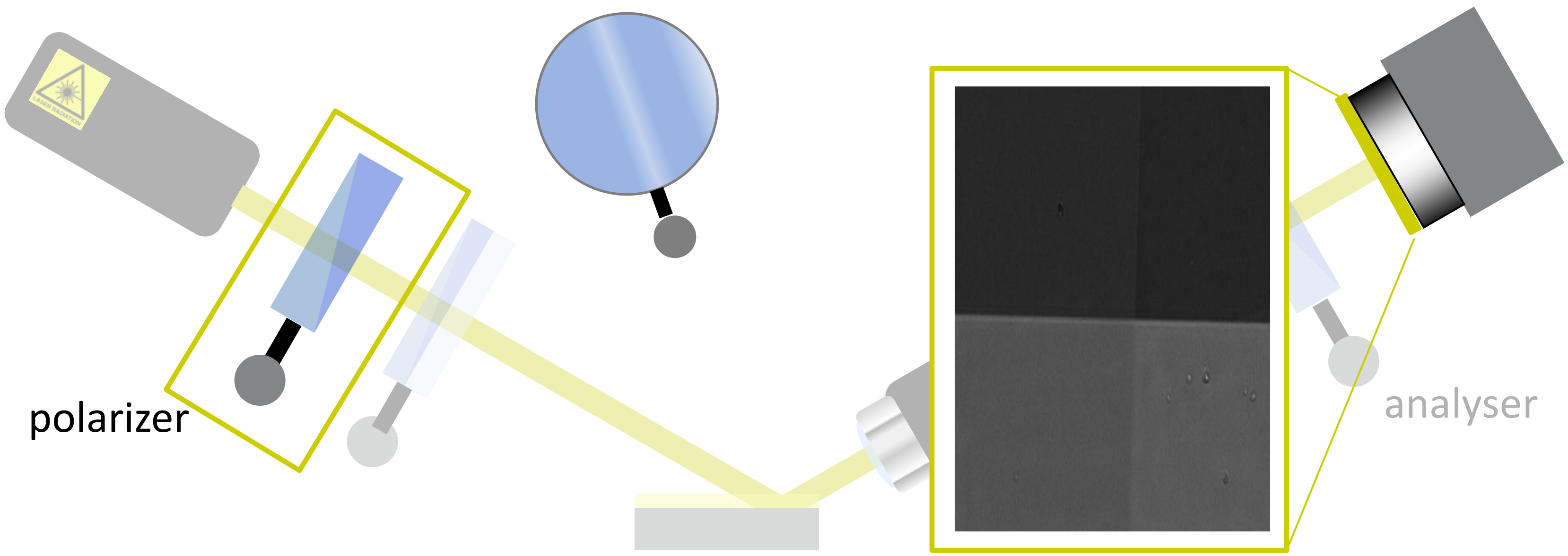

polarizer
analyser

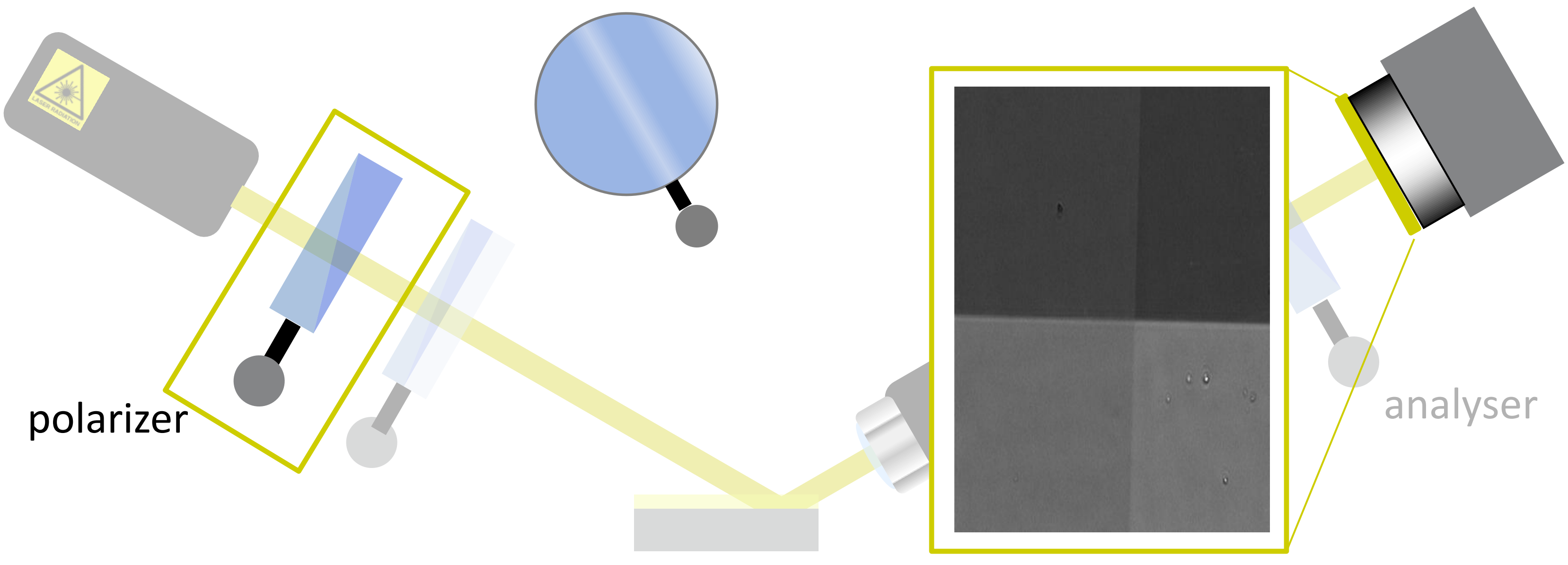

polarizer
analyser

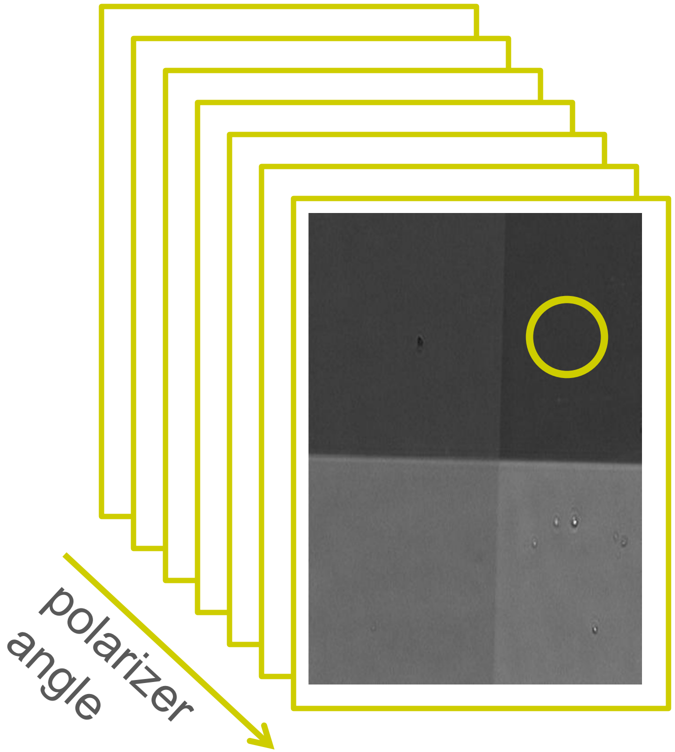

polarizer
analyser

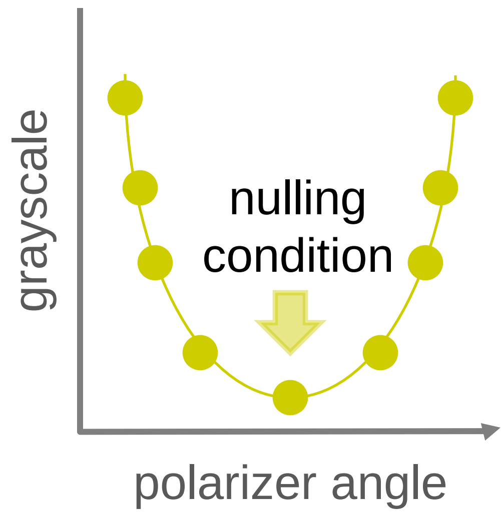

polarizer
analyser

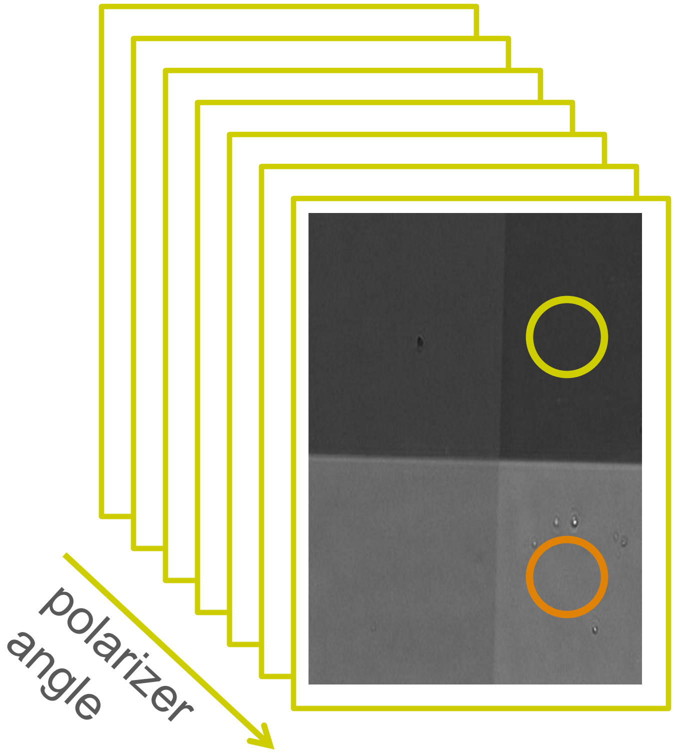

polarizer
analyser


polarizer
analyser

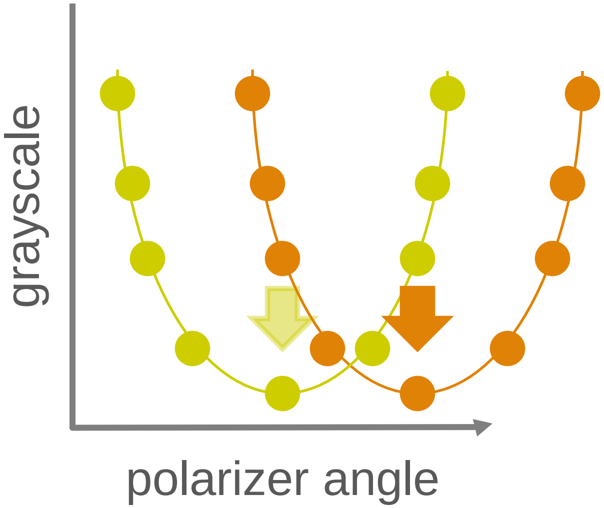

polarizer
analyser


polarizer
angle


grayscale
nulling
condition
polarizer angle

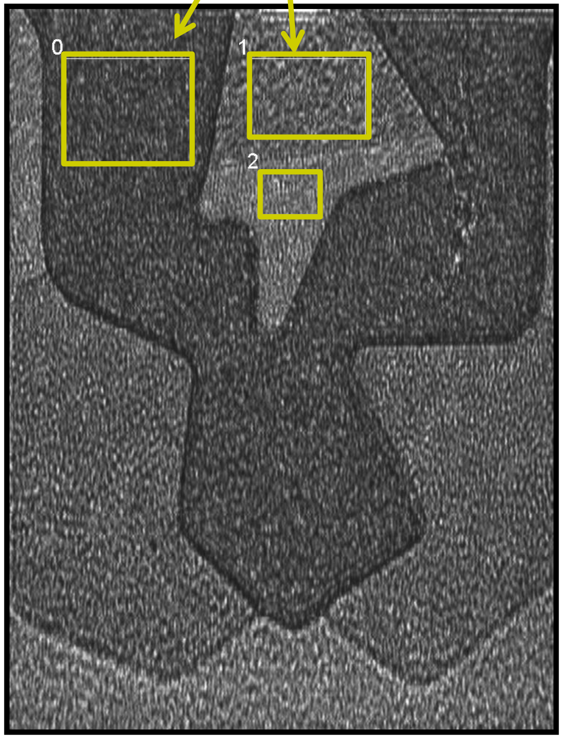


polarizer
angle



grayscale
polarizer angle

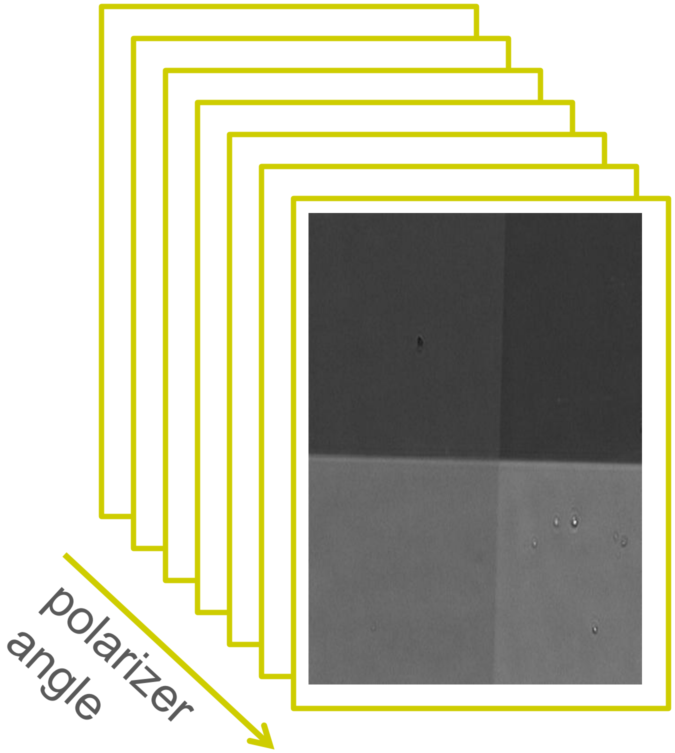
regions of interest



localized measurements of Δ,Ψ

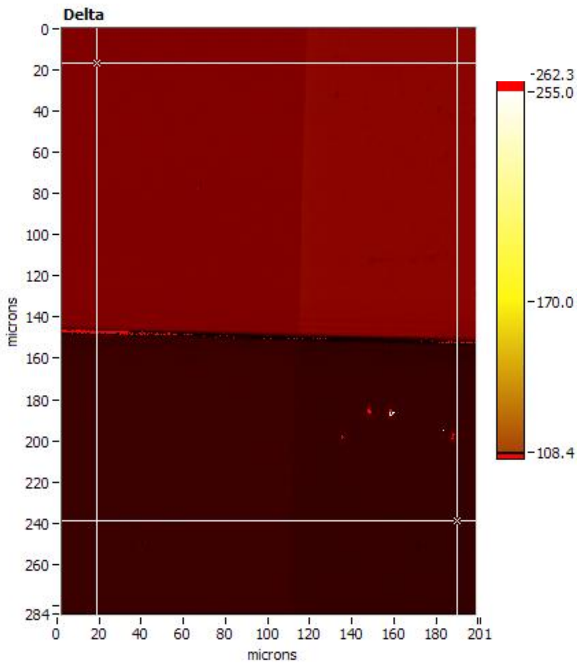
model

localized film thickness or optical properties



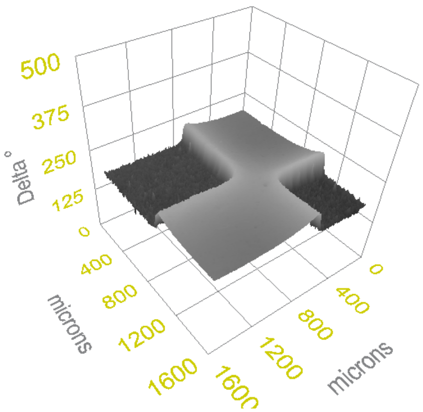
Evaluating all pixels :

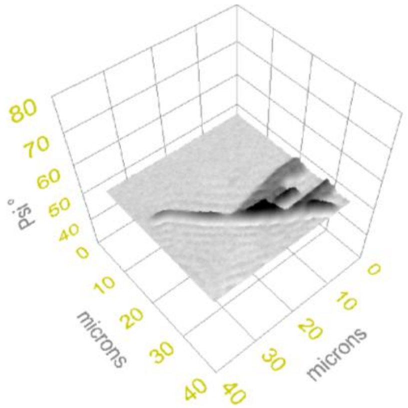
Δ map



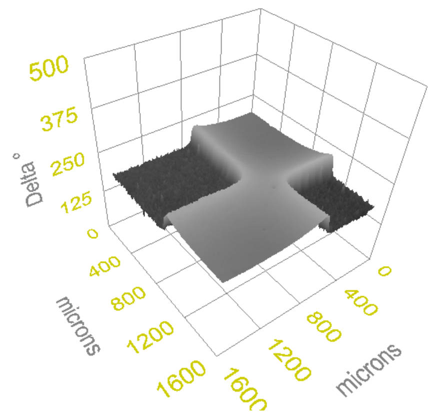
- analyzer: **Ψ map**

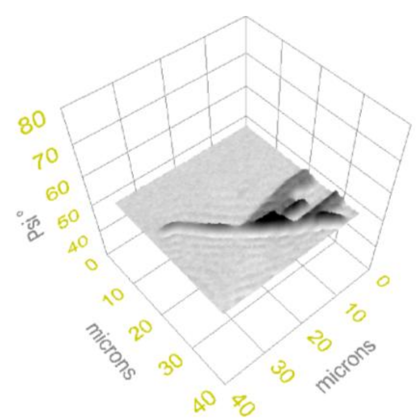
Δ, Ψ maps



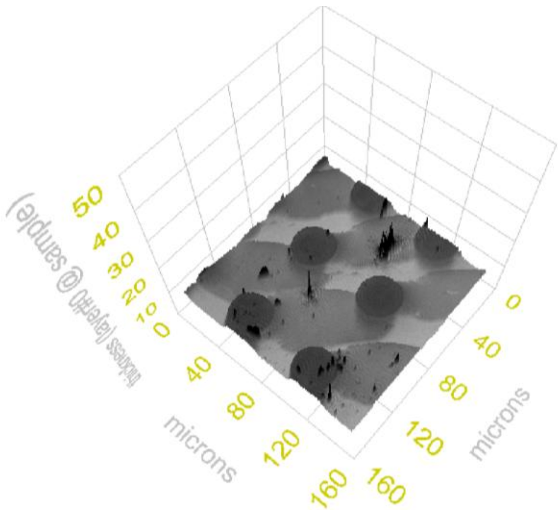


Δ, Ψ maps





Optical model



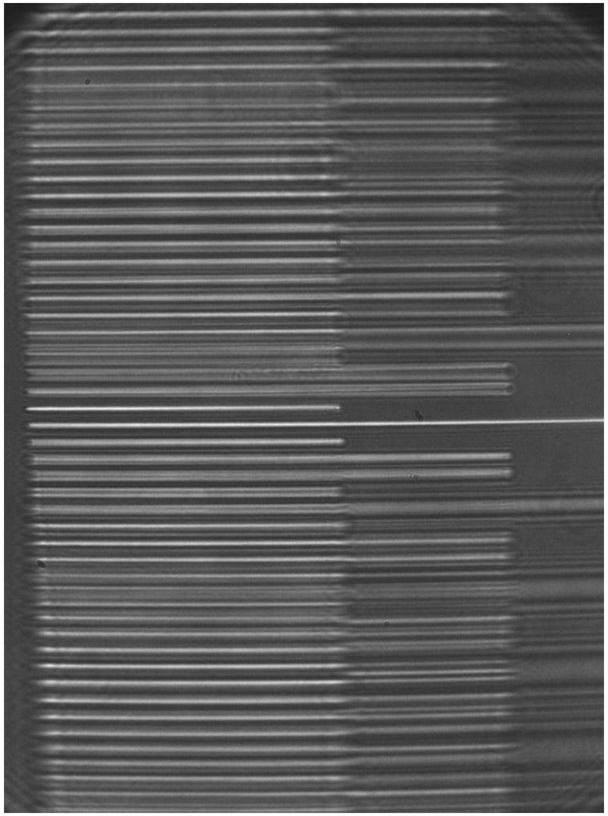
Result: thickness maps or maps of n, volume fraction etc.

- The depth-of-focus problem

– caused by the oblique imaging angle

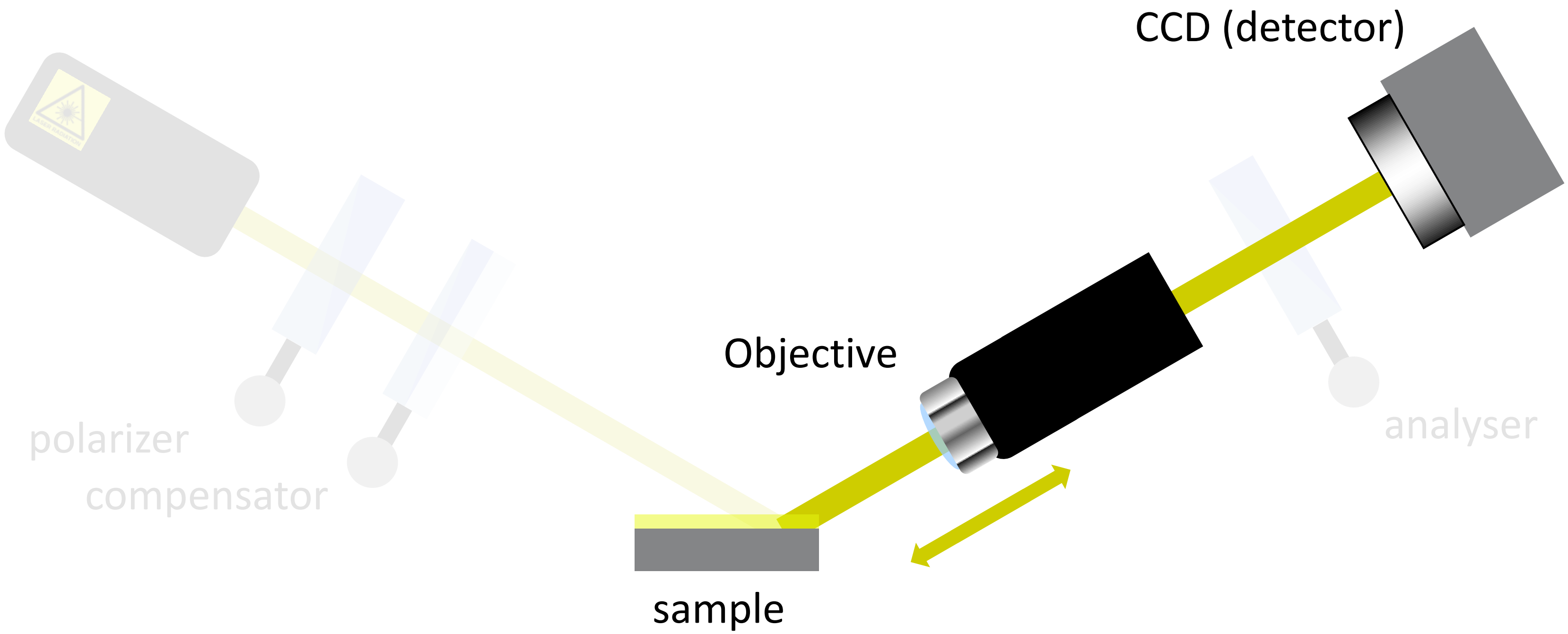
– with conventional optics, focus is achieved only in a narrow stripe.

Solution: mechanical *focus scanning*
+ image processing

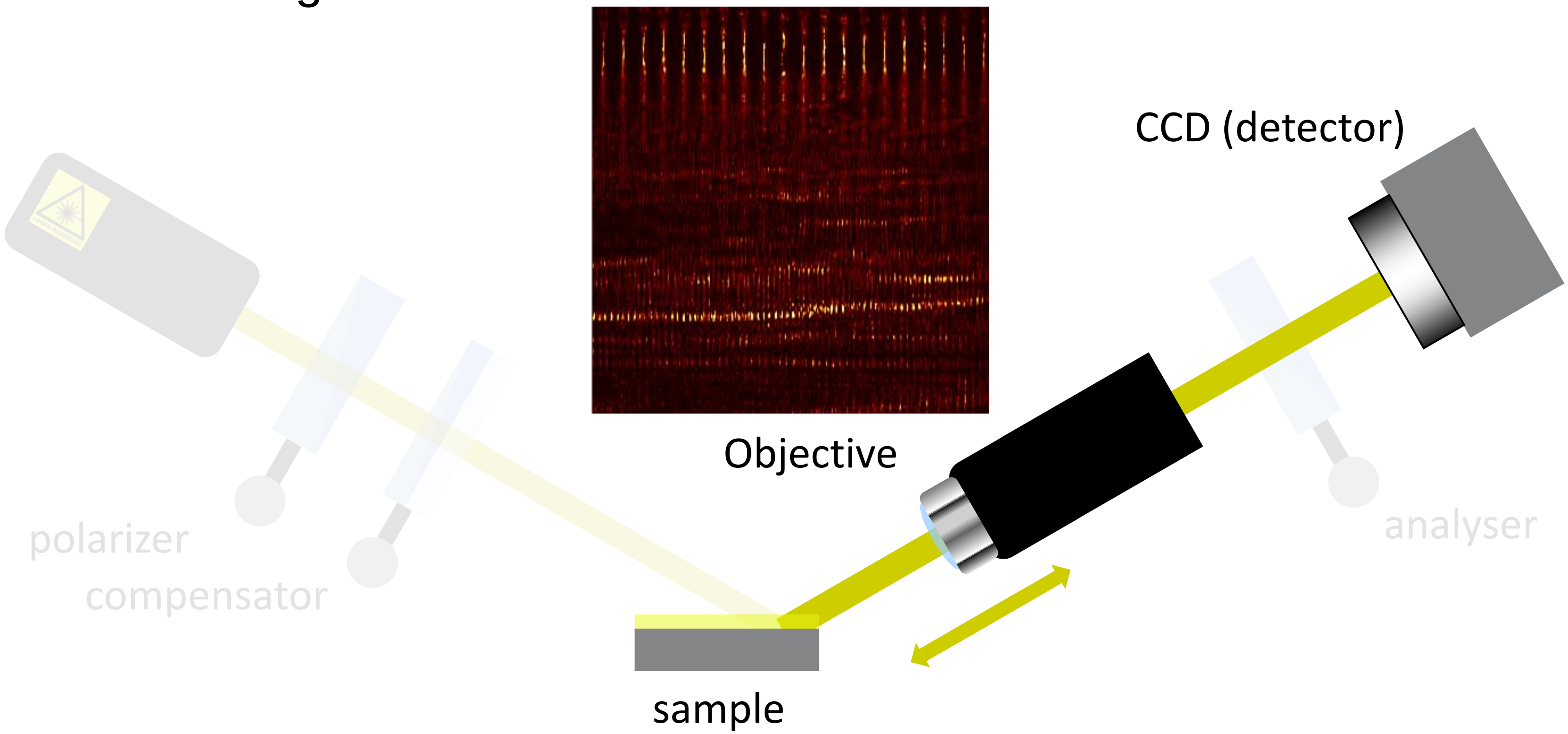


focus

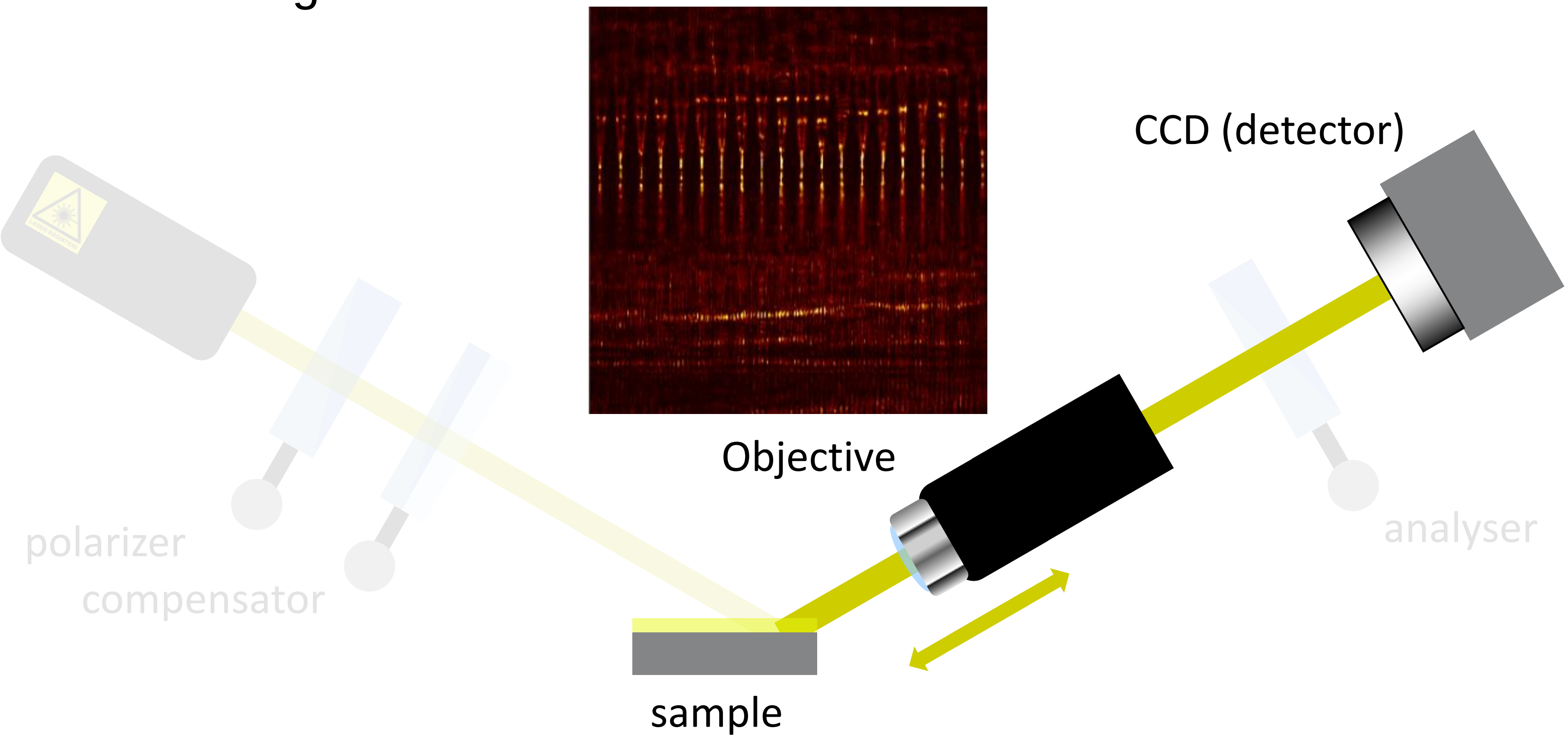
focus scanning



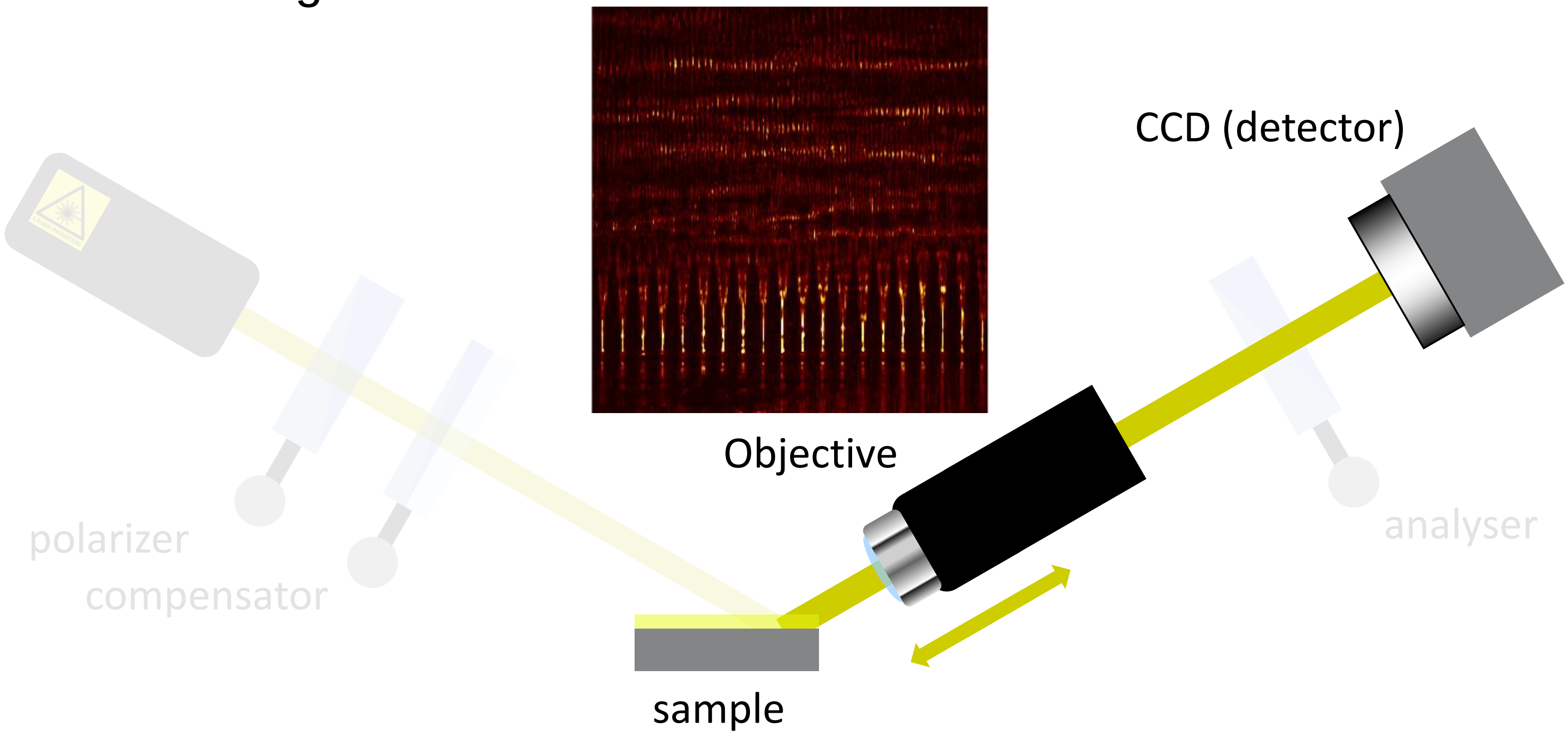
focus scanning



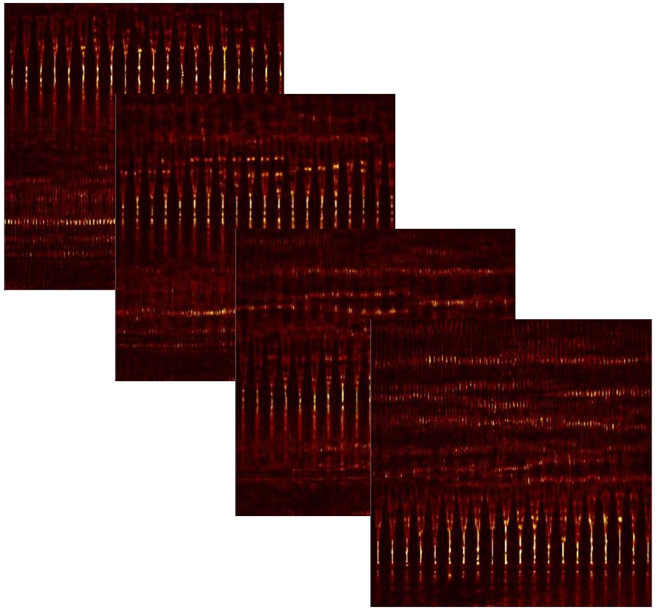
focus scanning

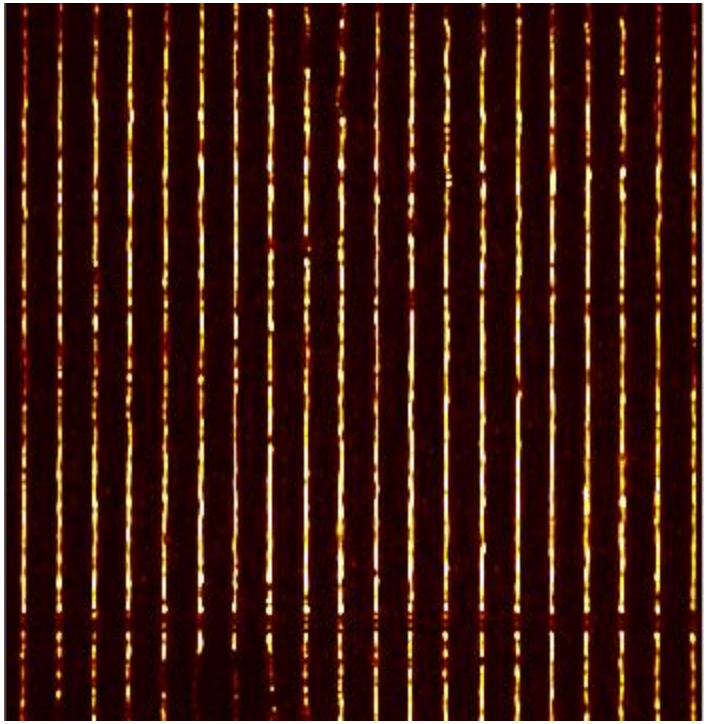


focus scanning



focus scanning + image processing:

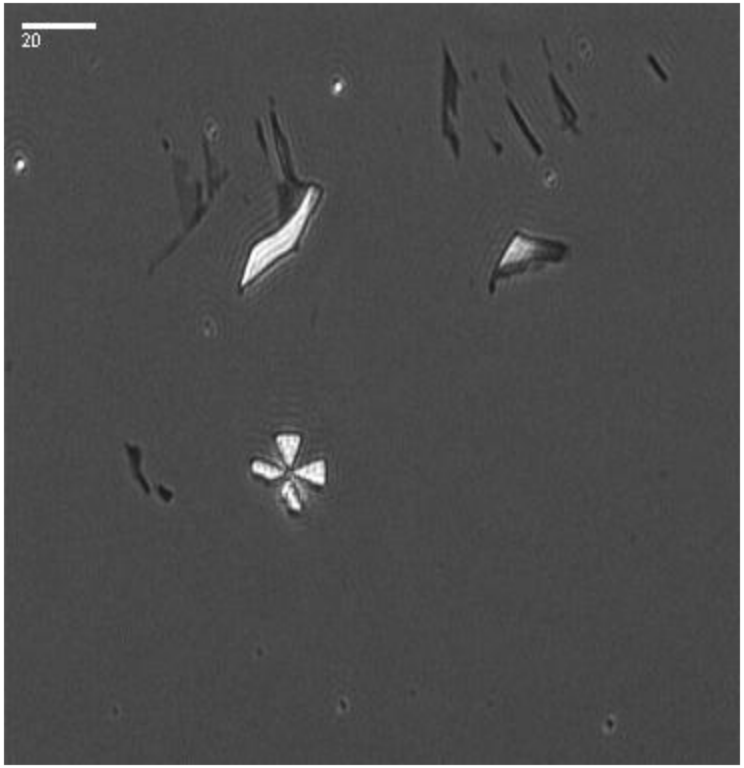




- Pinpointing and identification

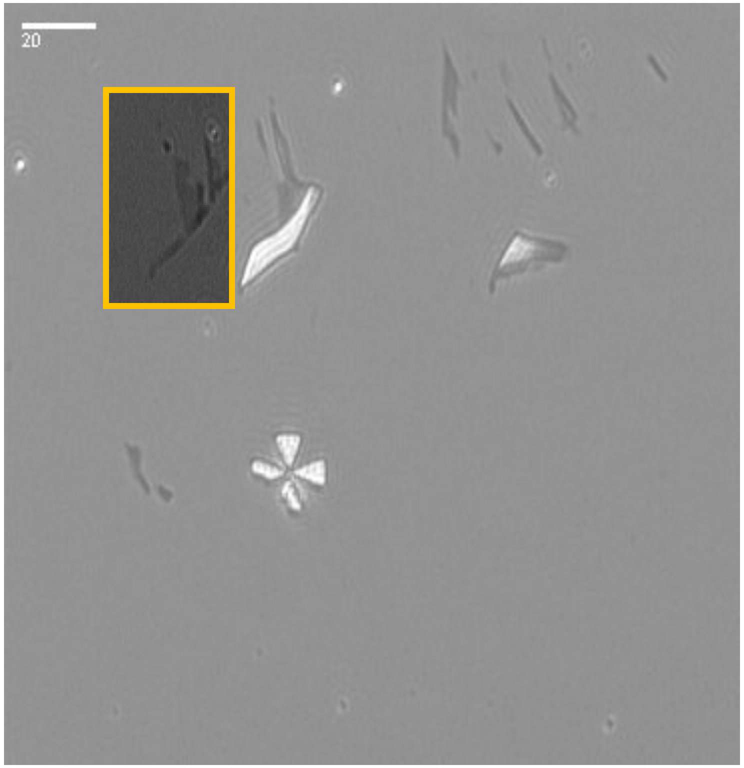
- Pinpointing and identification

  Ellipsometric contrast micrographs



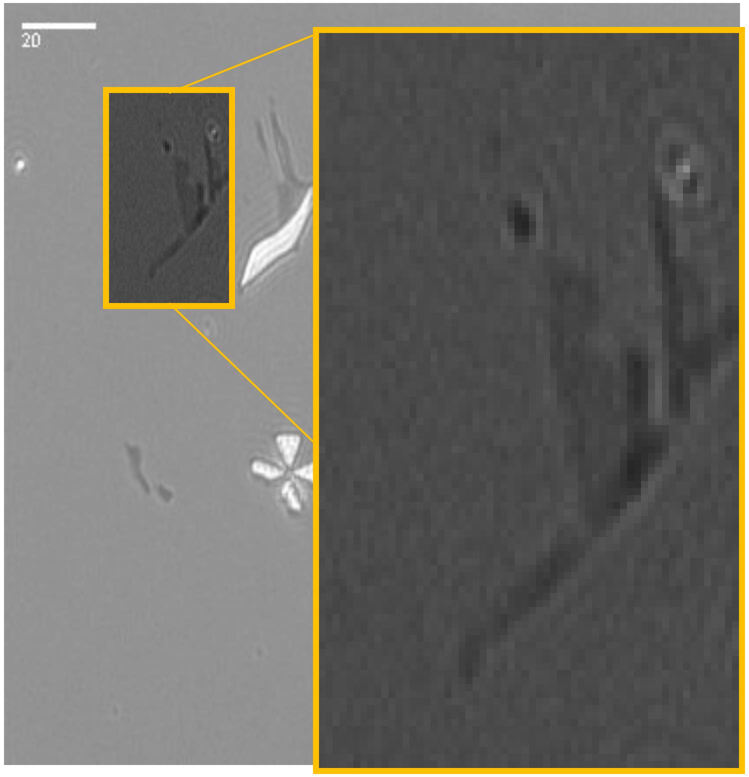
- Pinpointing and identification

Ellipsometric contrast micrographs



- Pinpointing and identification

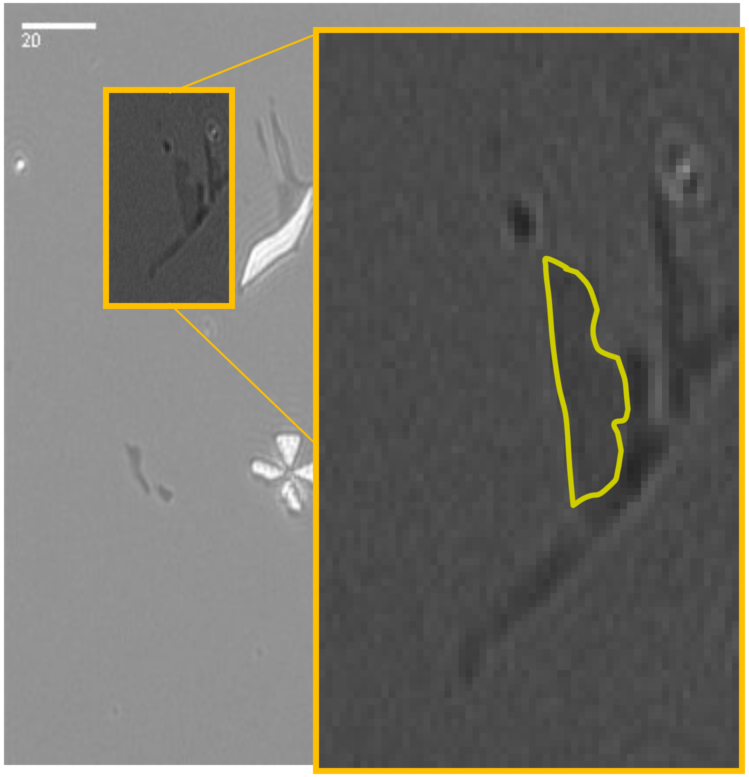
Ellipsometric contrast micrographs



Graphene monolayer

- Pinpointing and identification

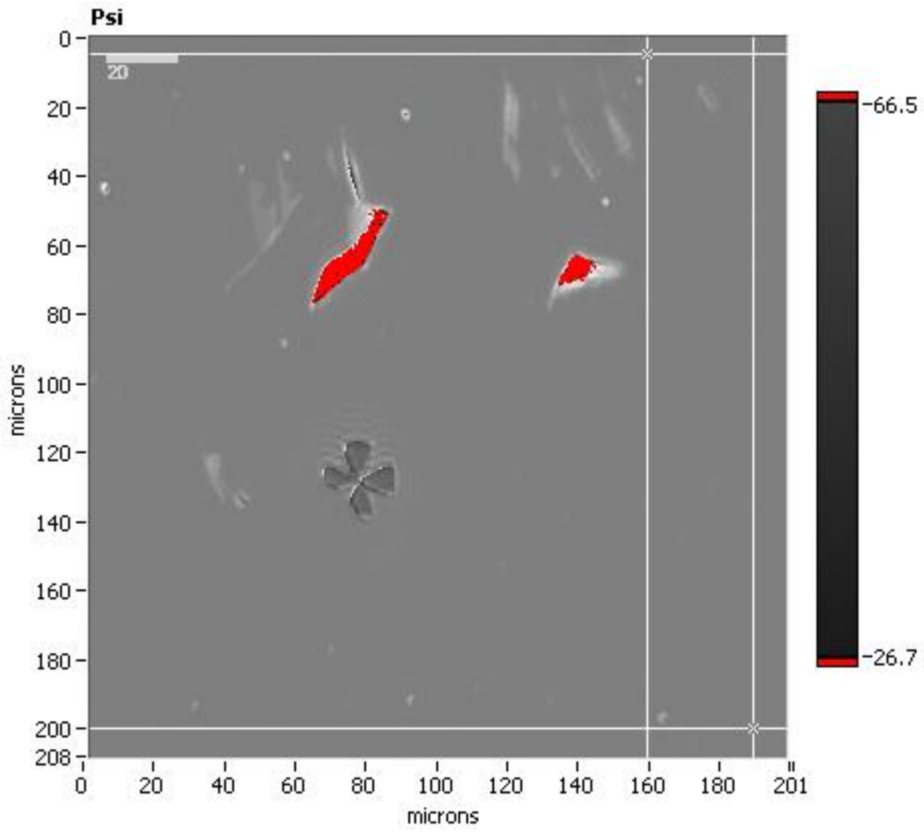
Ellipsometric contrast micrographs



Graphene monolayer

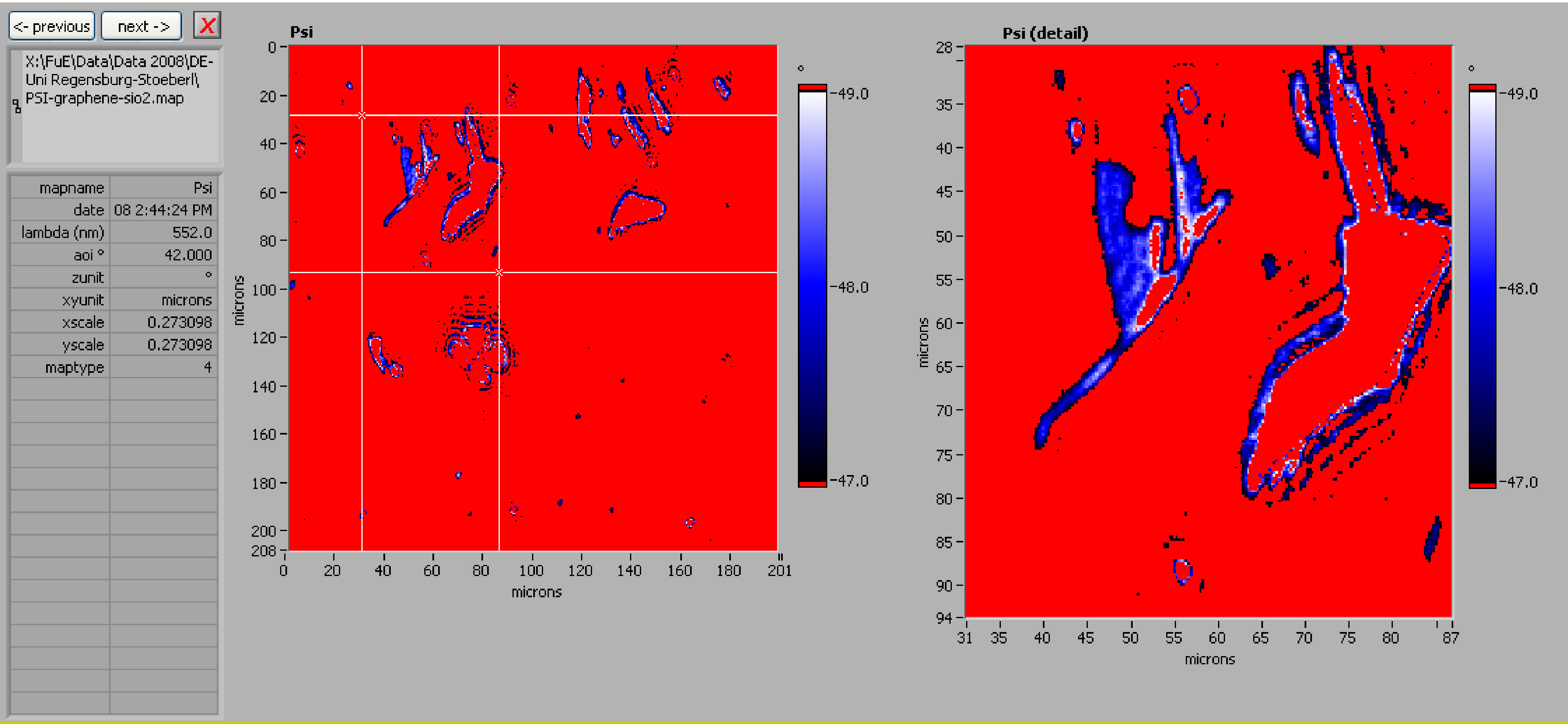
- Pinpointing and identification

  Psi-map



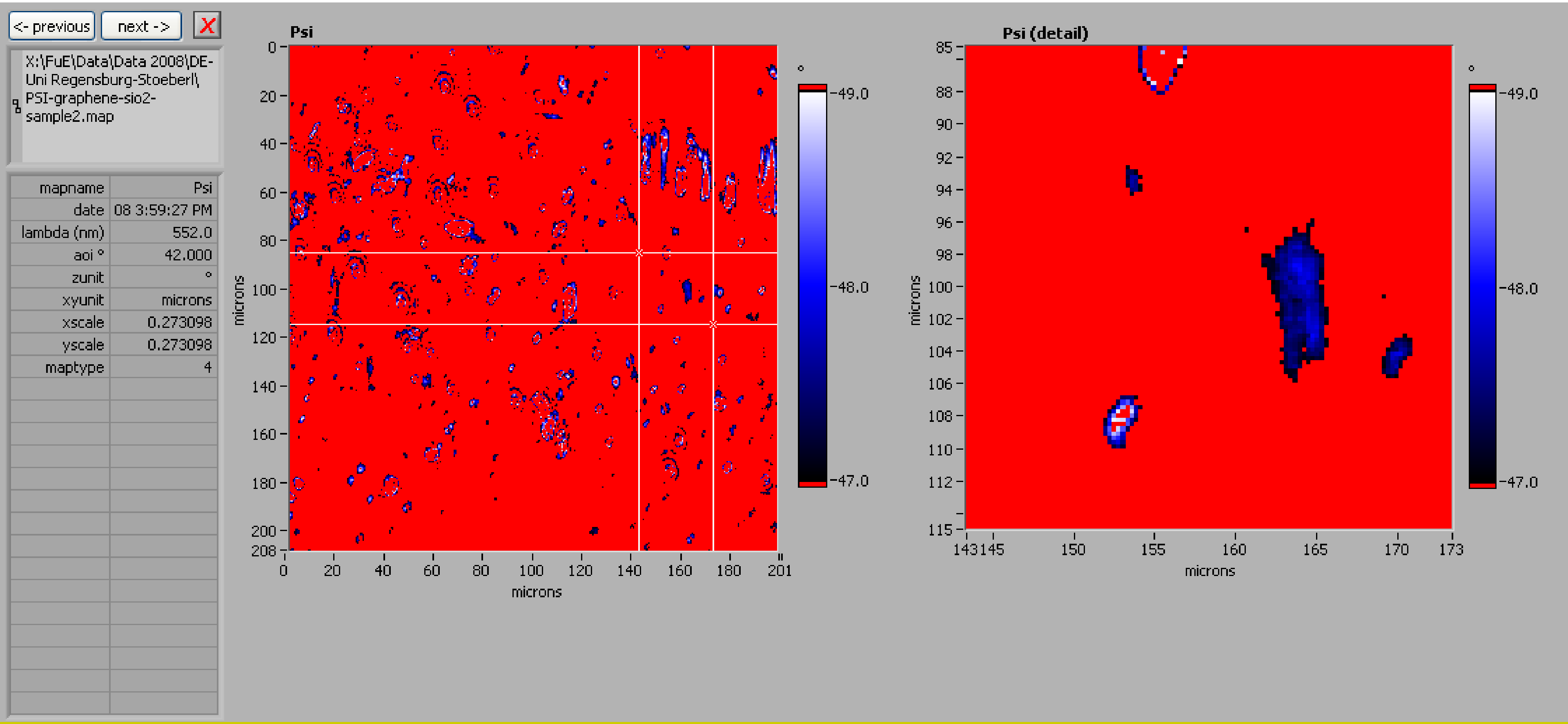
Pinpointing and identification

Psi-map



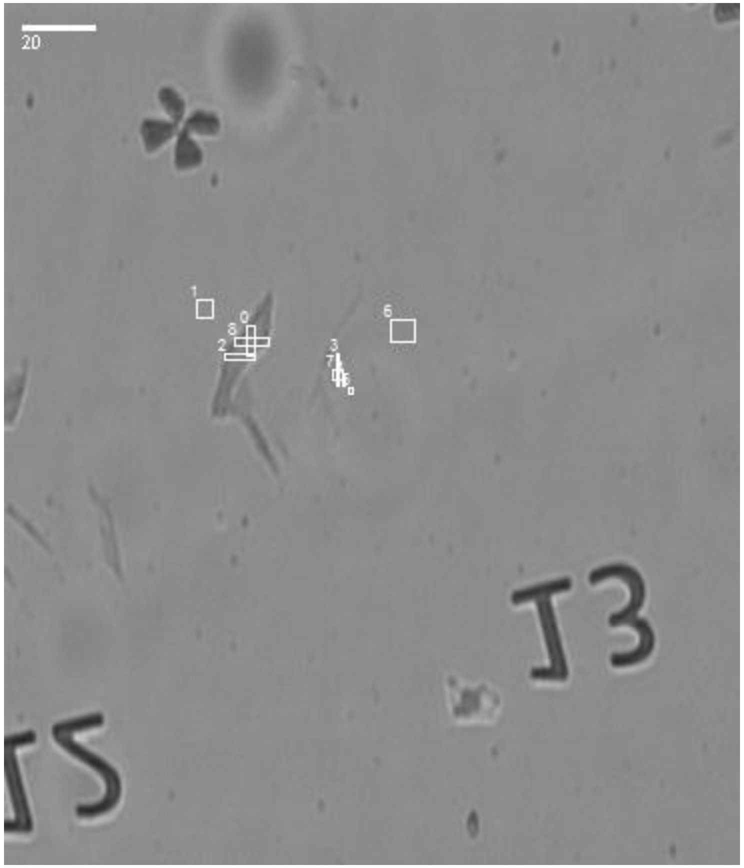
Pinpointing and identification

Psi-map



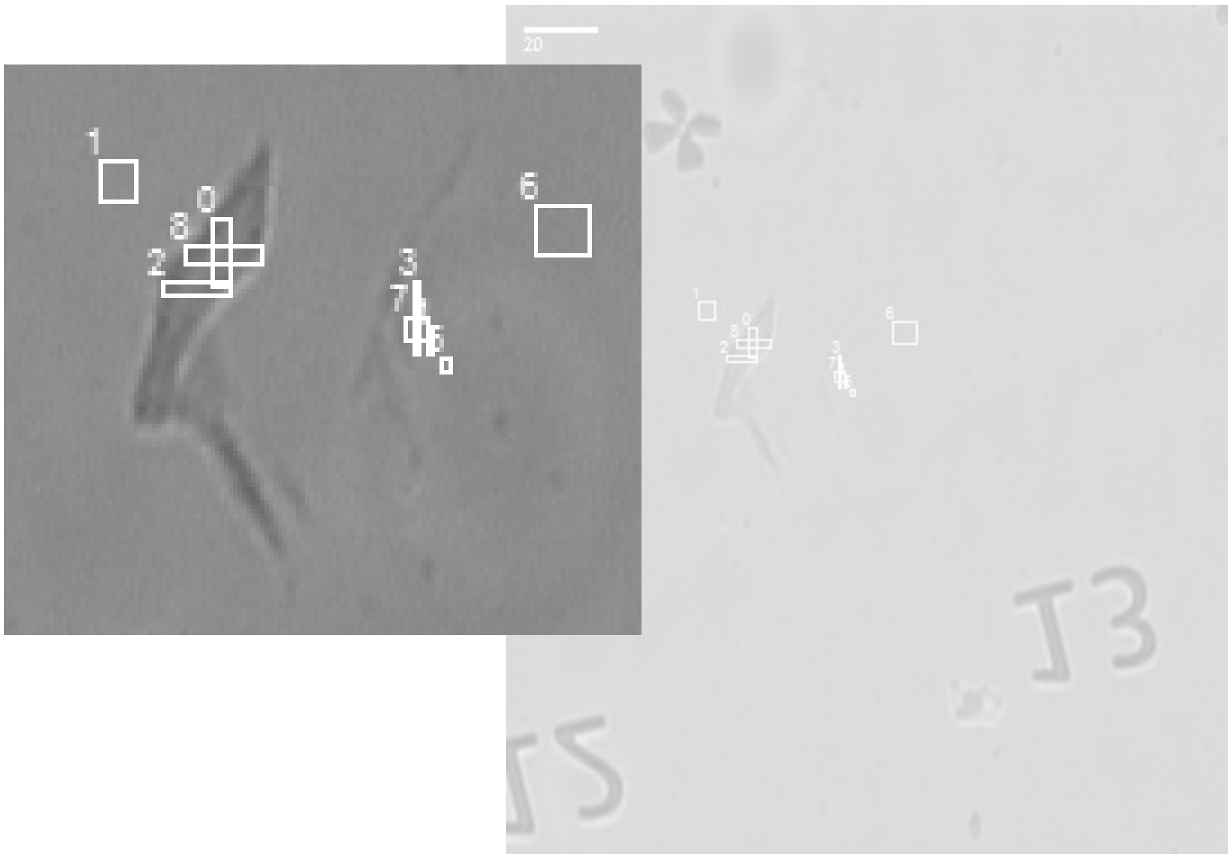
- ellipsometric characterization

Variable angle imaging spectroscopic ellipsometry

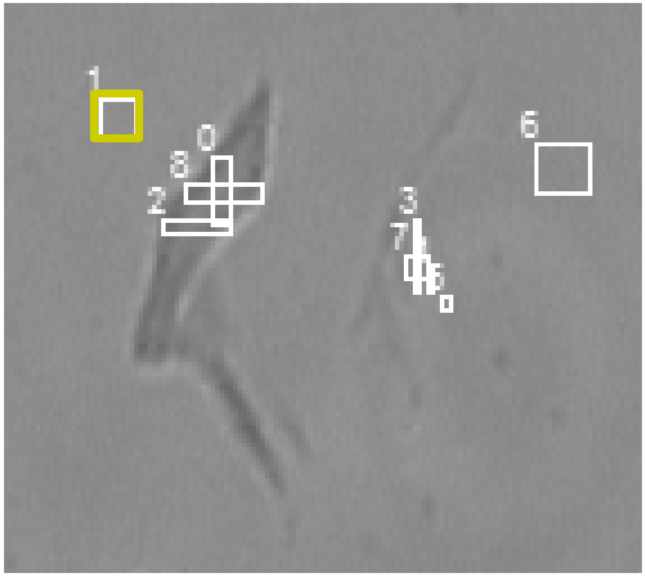


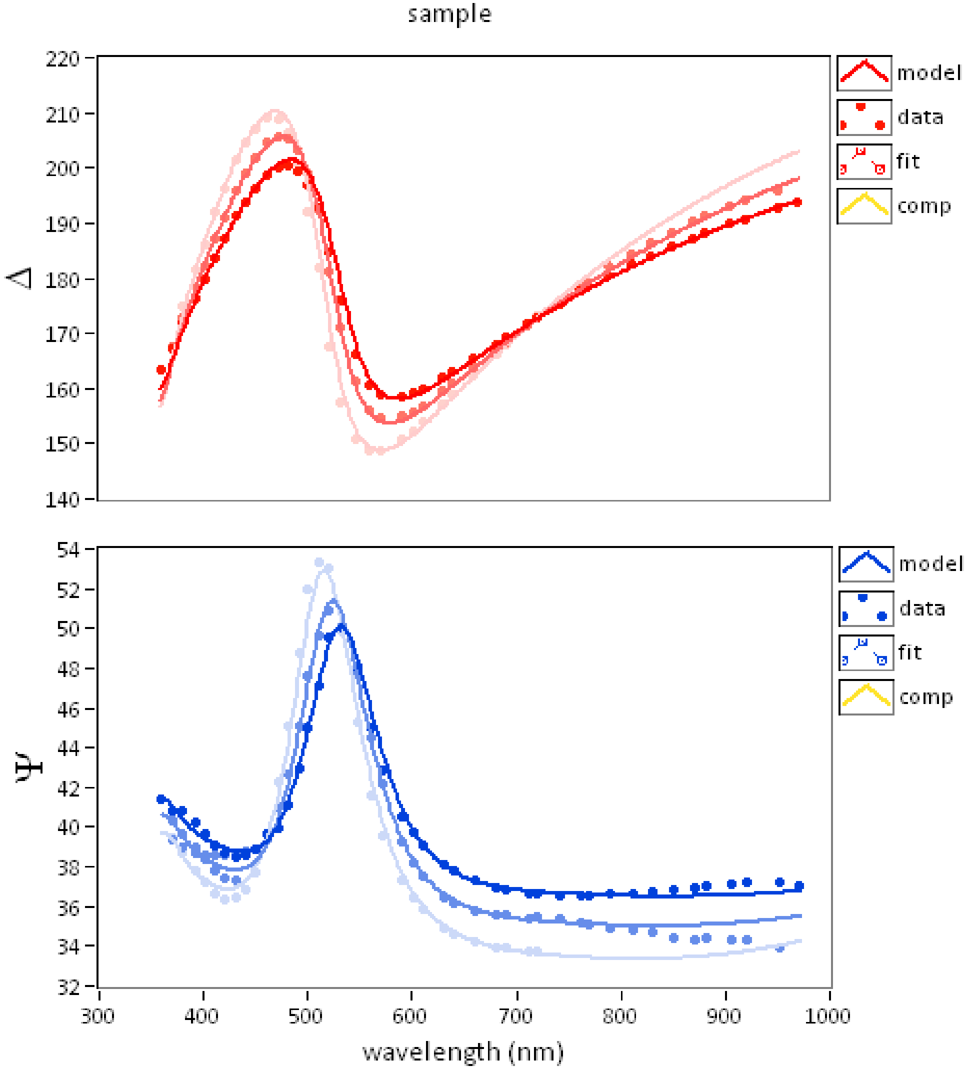
- ellipsometric characterization

Variable angle imaging spectroscopic ellipsometry

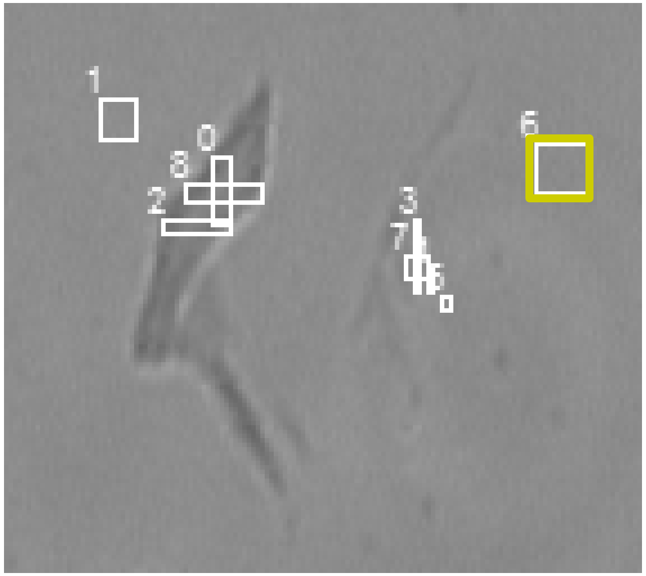


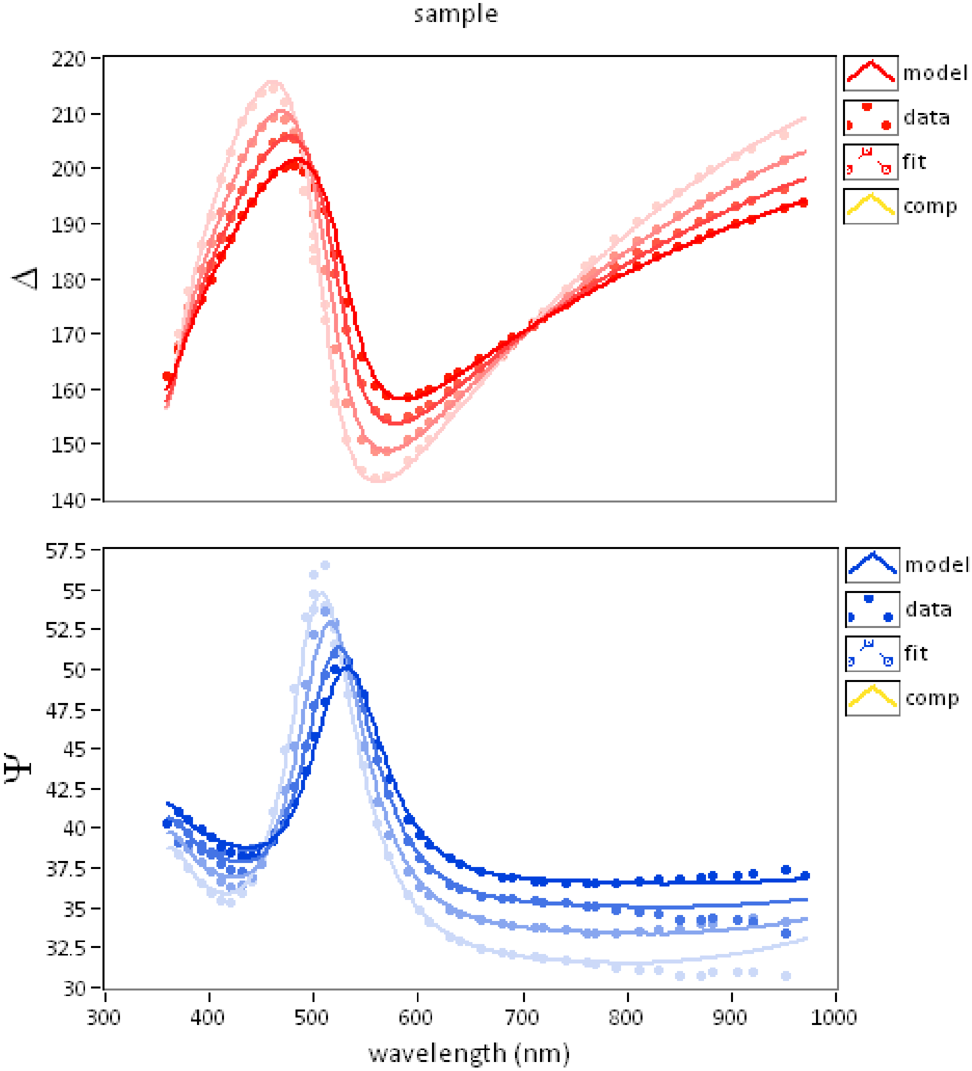
ROI 1


1
0
8
2
3
7
5
6

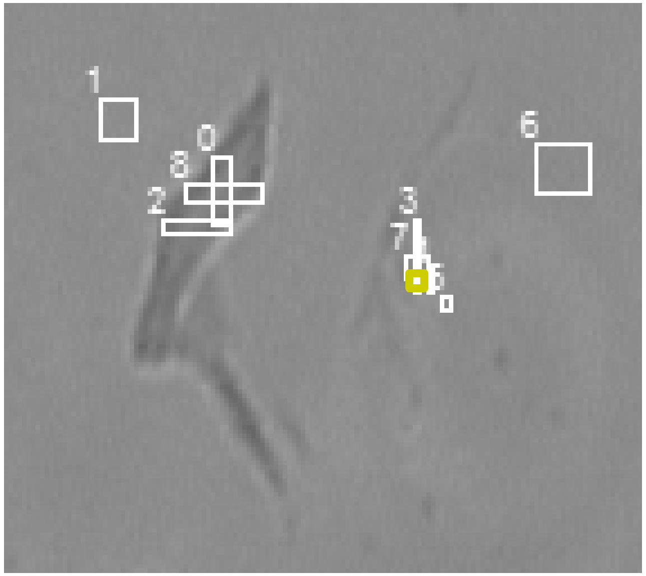

sample
220
210
200
190
180
170
160
150
140
Δ
model
data
fit
comp
54
52
50
48
46
44
42
40
38
36
34
32
Ψ
300
400
500
600
700
800
900
1000
wavelength (nm)

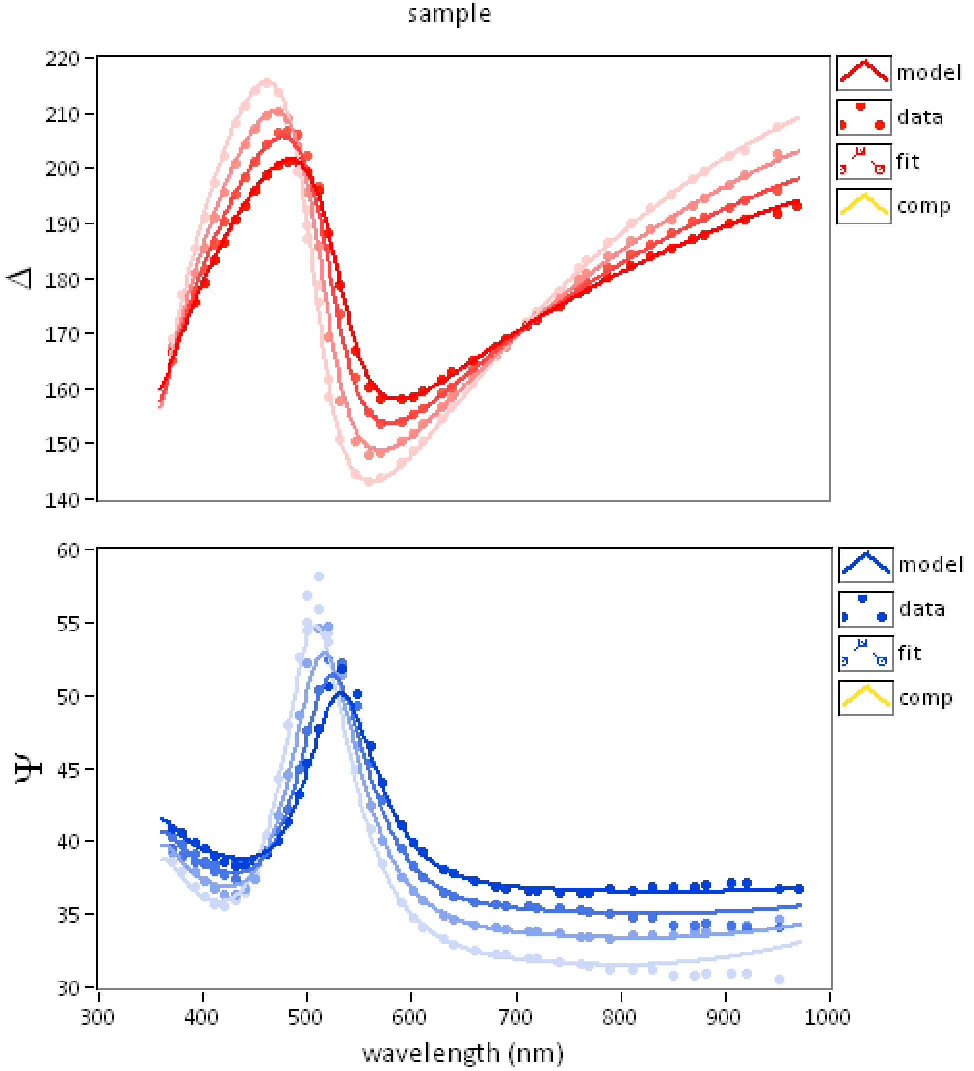
ROI 6


1
0
8
2
3
7
5
6

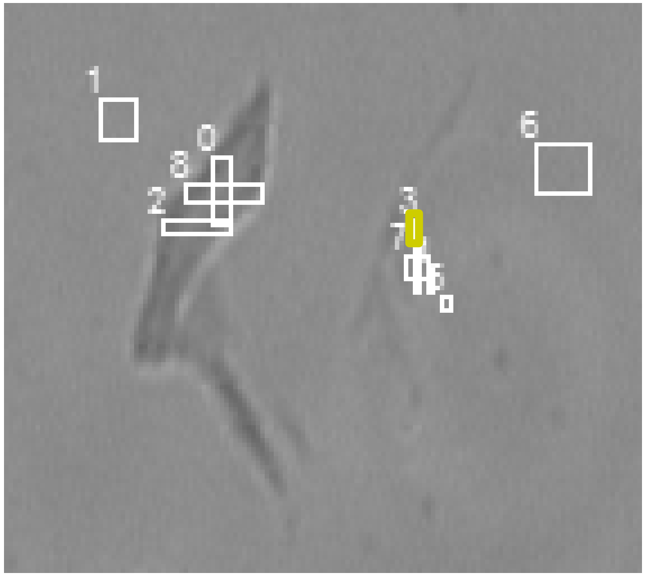

sample
Δ
220
210
200
190
180
170
160
150
140
model
data
fit
comp
Ψ
57.5
55
52.5
50
47.5
45
42.5
40
37.5
35
32.5
30
300
400
500
600
700
800
900
1000
wavelength (nm)

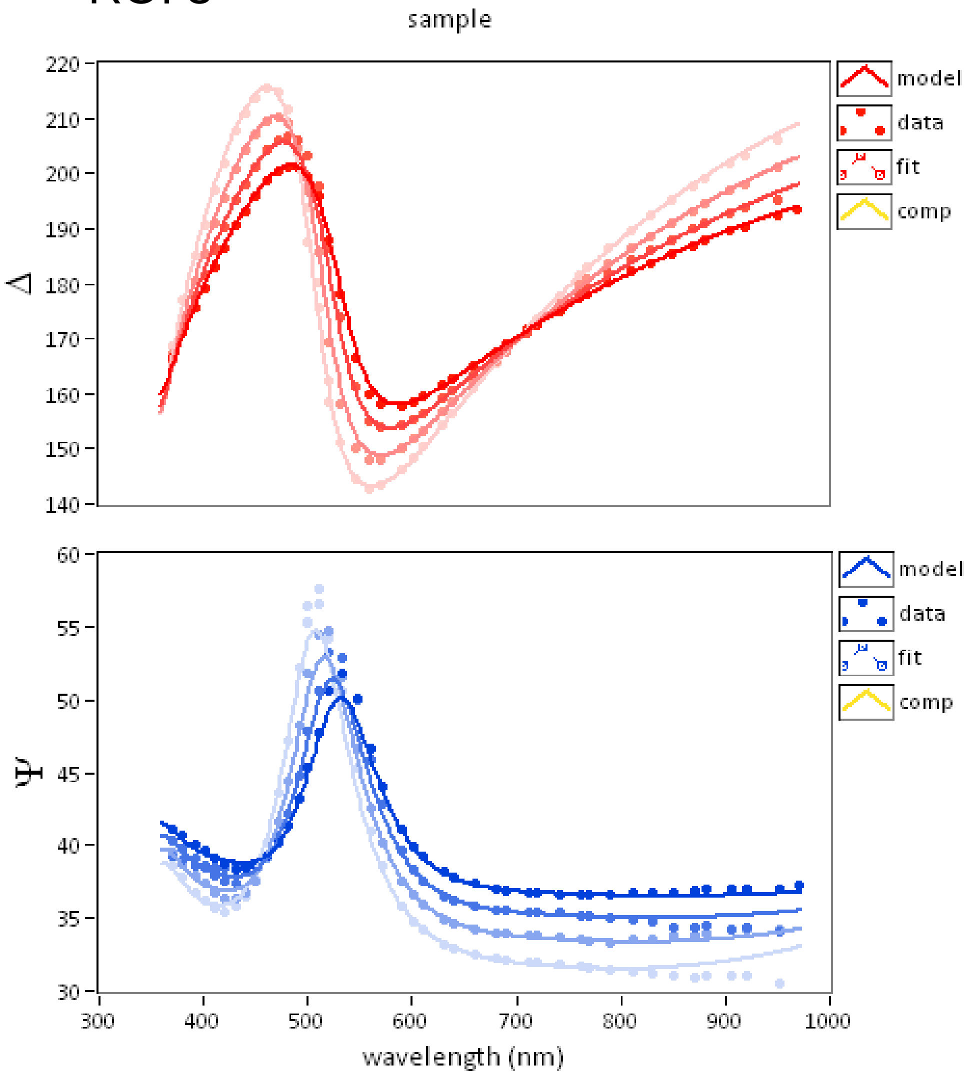
ROI 4


1
0
8
2
3
7
5
6

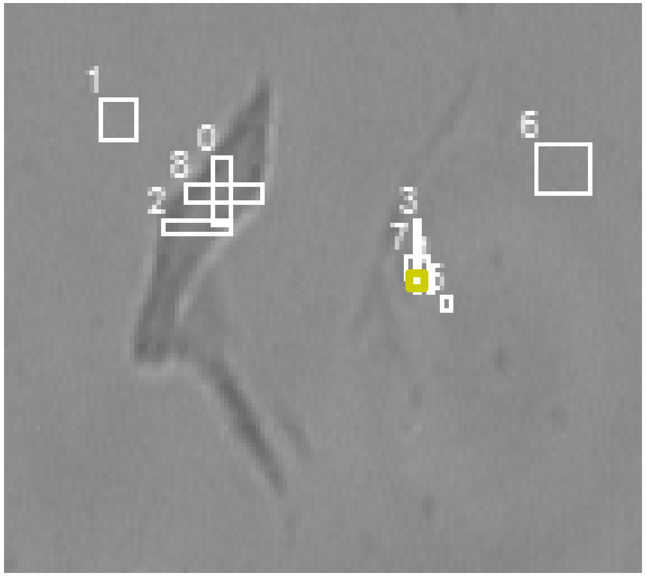

sample
Δ
220
210
200
190
180
170
160
150
140
model
data
fit
comp
Ψ
60
55
50
45
40
35
30
300
400
500
600
700
800
900
1000
wavelength (nm)

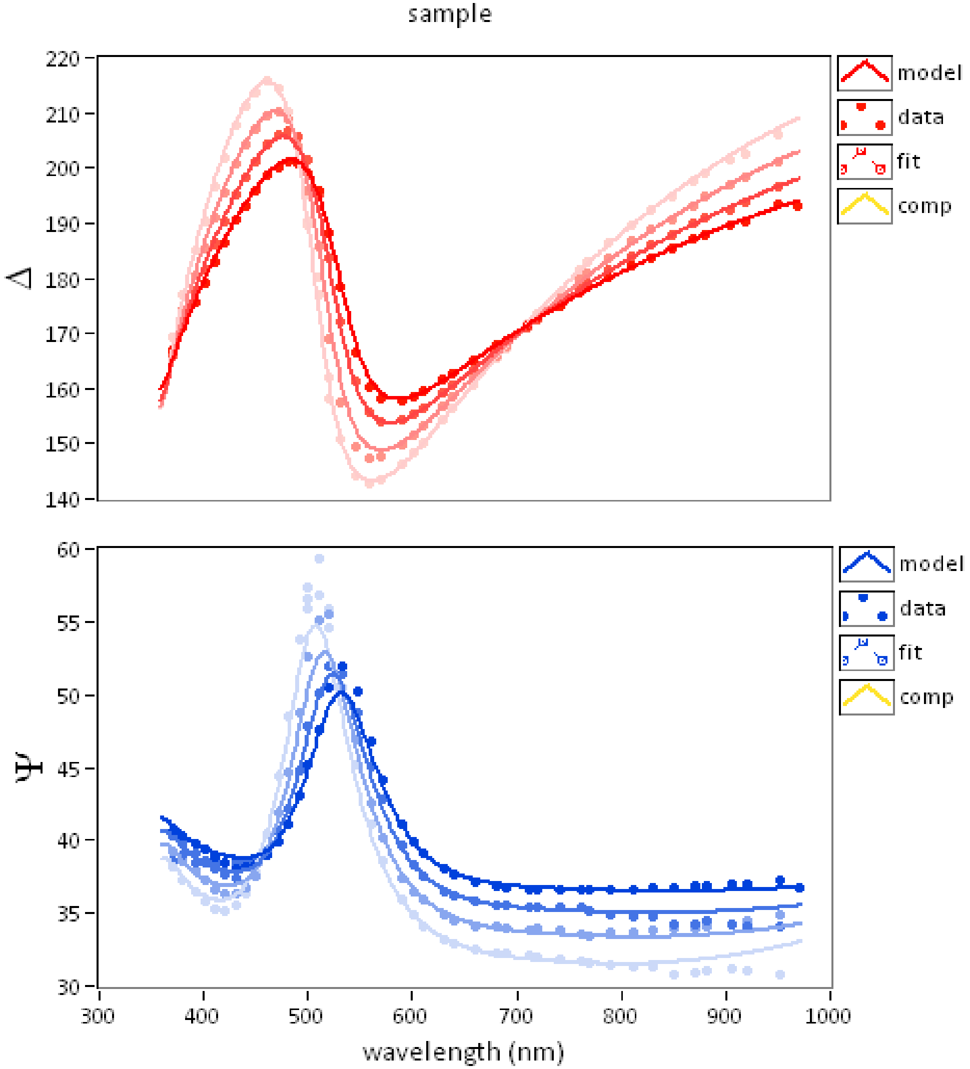
ROI 3



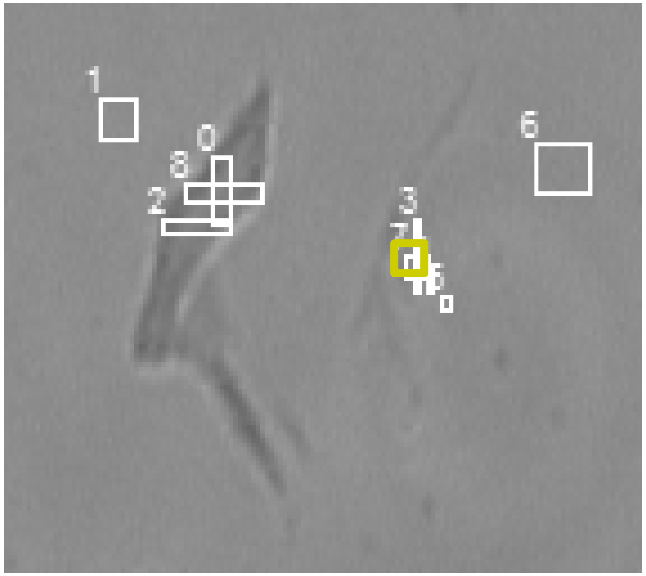


ROI 5

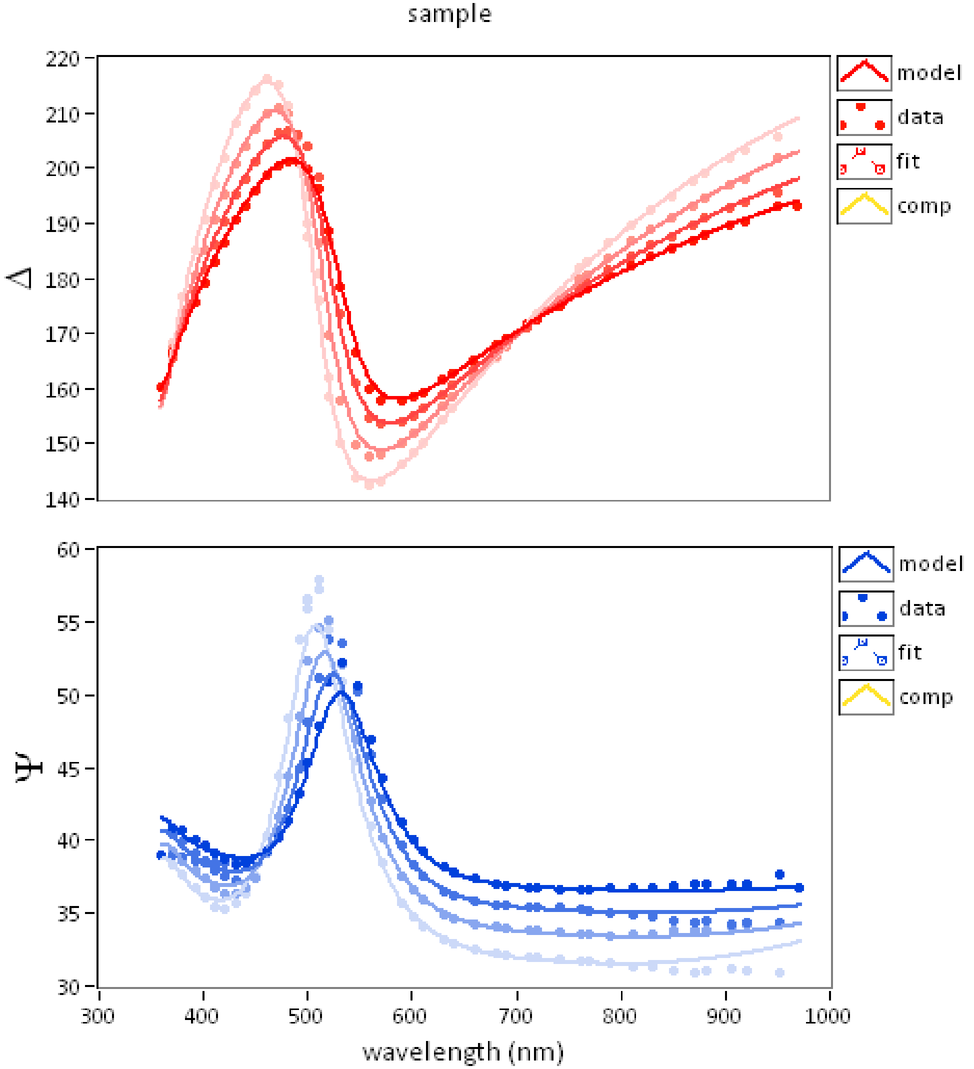

1
0
8
2
3
7
5
6


sample
220
210
200
190
180
170
160
150
140
Δ
model
data
fit
comp
60
55
50
45
40
35
30
Ψ
model
data
fit
comp
300
400
500
600
700
800
900
1000
wavelength (nm)

ROI 7

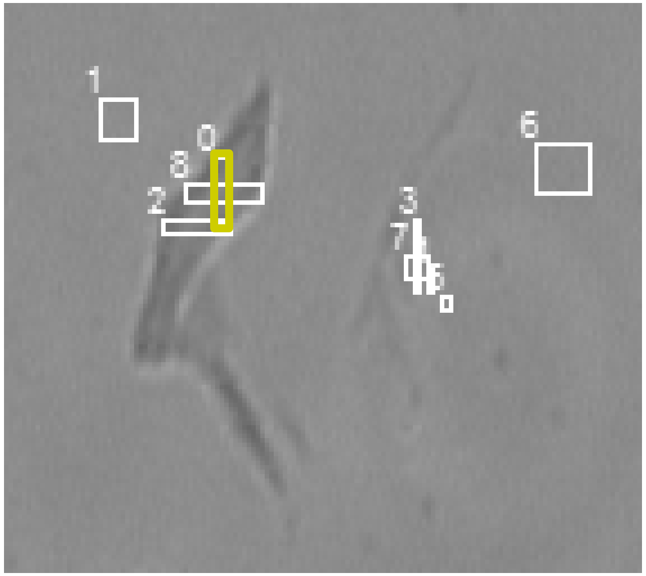


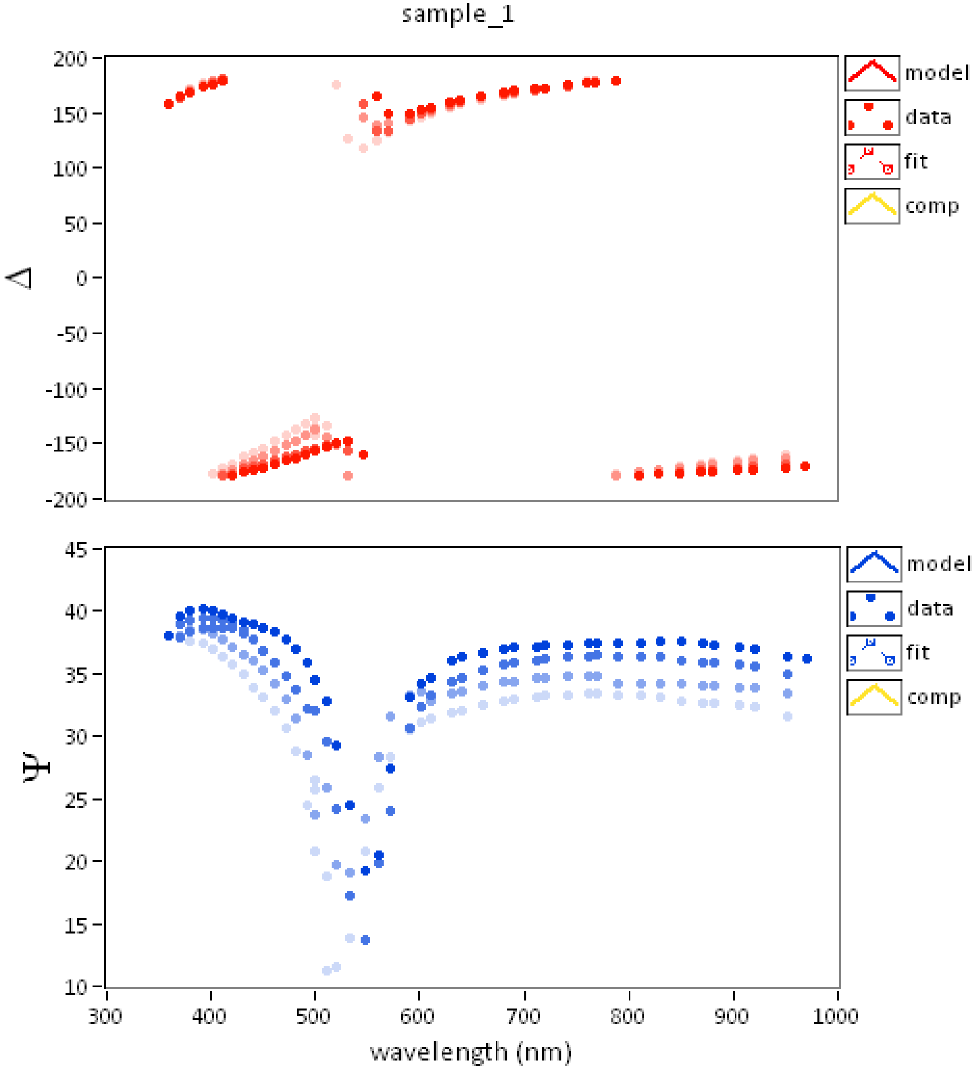
1
0
8
2
3
7
5
6

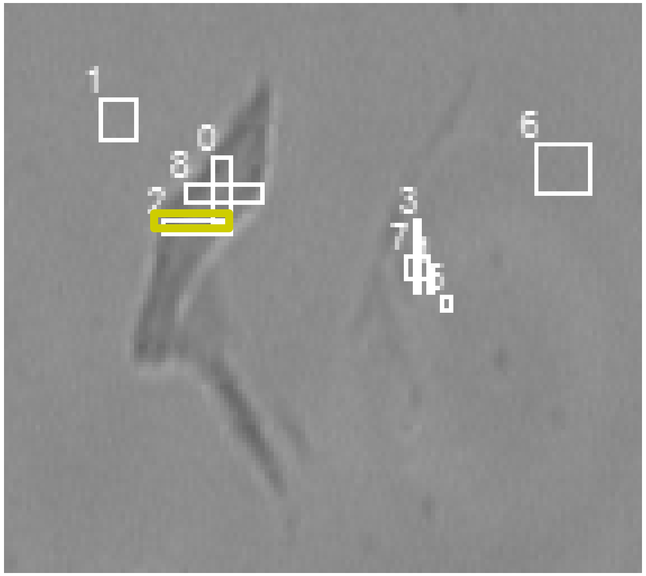


sample
Δ
220
210
200
190
180
170
160
150
140
model
data
fit
comp
Ψ
60
55
50
45
40
35
30
300
400
500
600
700
800
900
1000
wavelength (nm)

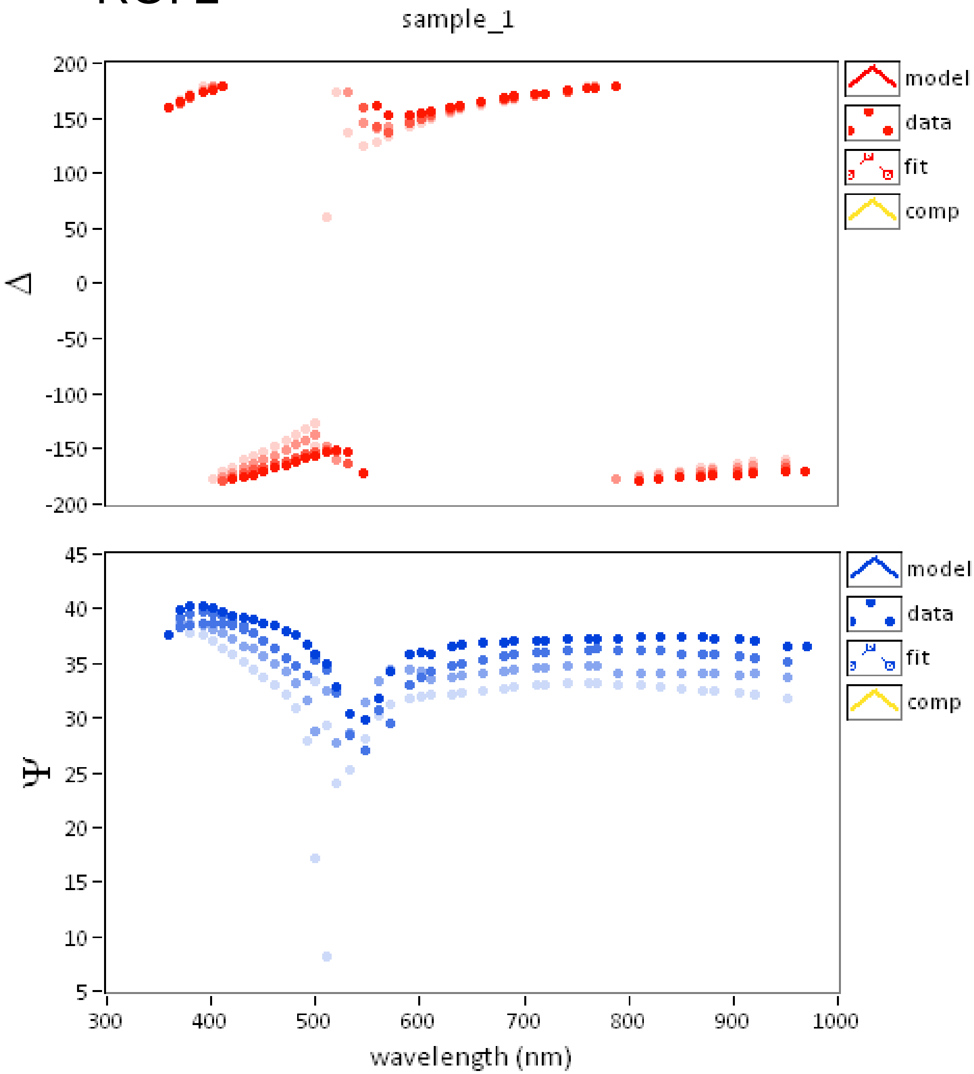
ROI 0


1
0
8
2
3
7
5
6

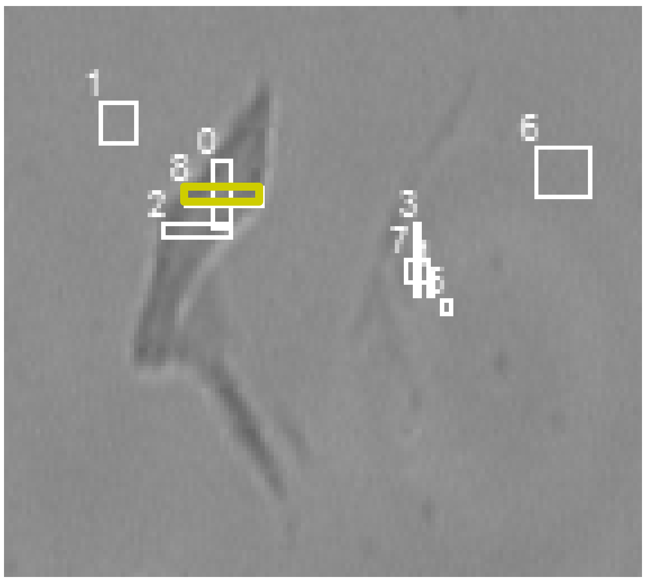

sample_1
Δ
Ψ
model
data
fit
comp
wavelength (nm)
200
150
100
50
0
-50
-100
-150
-200
45
40
35
30
25
20
15
10
300
400
500
600
700
800
900
1000

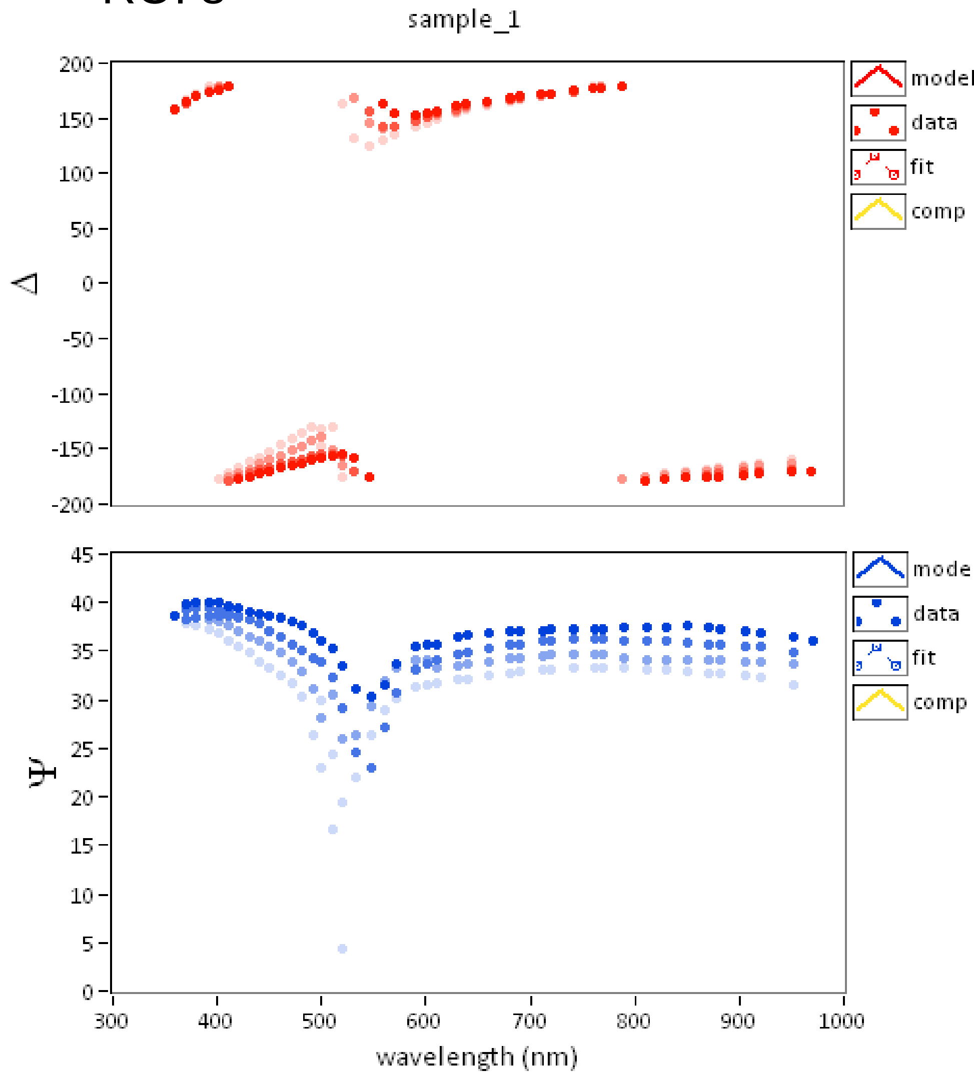


ROI 2



ROI 8


1
0
8
2
3
7
6


sample_1
Δ
Ψ
wavelength (nm)
model
data
fit
comp
200
150
100
50
0
-50
-100
-150
-200
45
40
35
30
25
20
15
10
5
0
300
400
500
600
700
800
900
1000

- ellipsometric characterization

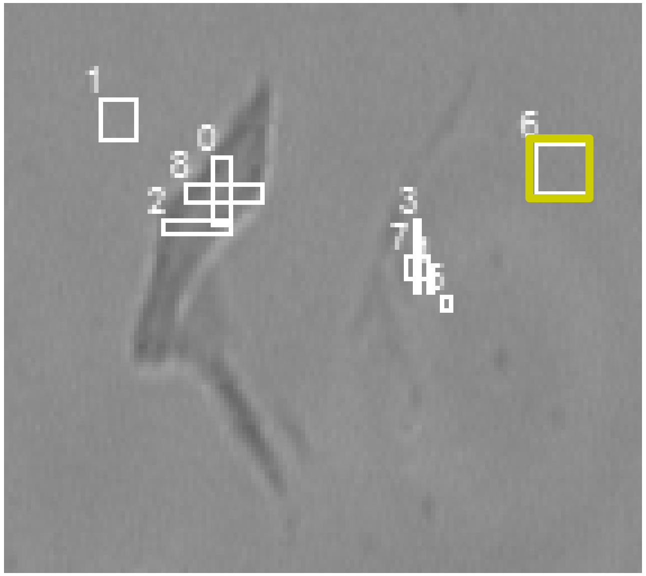
  data evaluation

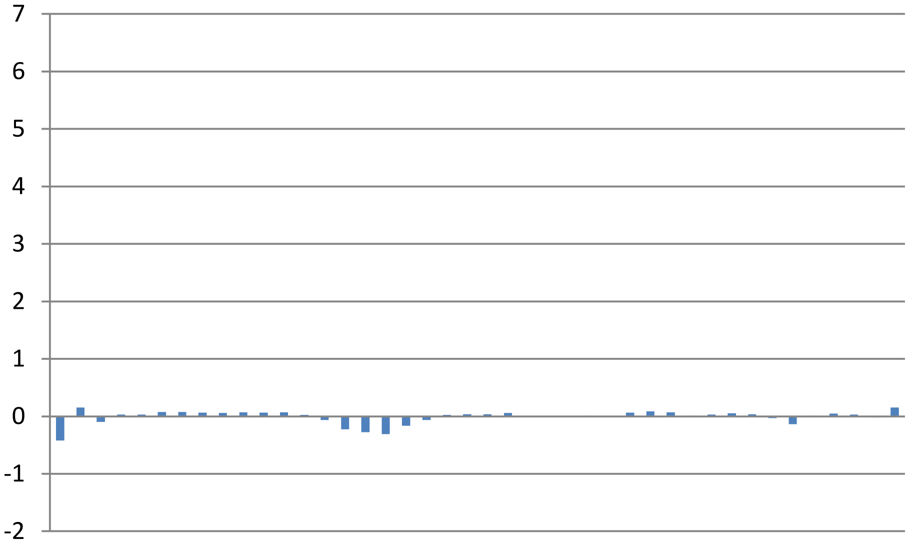
The spectra of graphene and of the substrate seem to be very similar. The differences between substrate ROIs and a refence ROI and between graphene ROIs the reference ROI are significantly unlike each user.

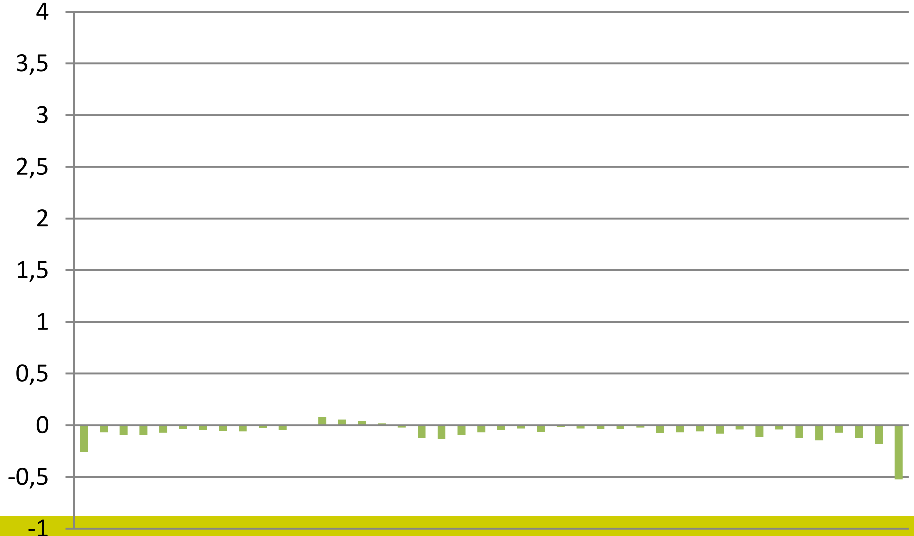
= RoI 6 - Reference RoI

AOI = 43 °

substrate



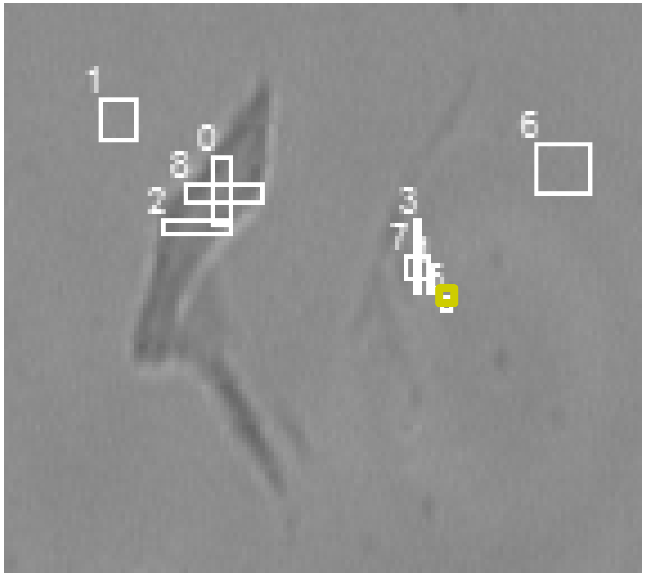


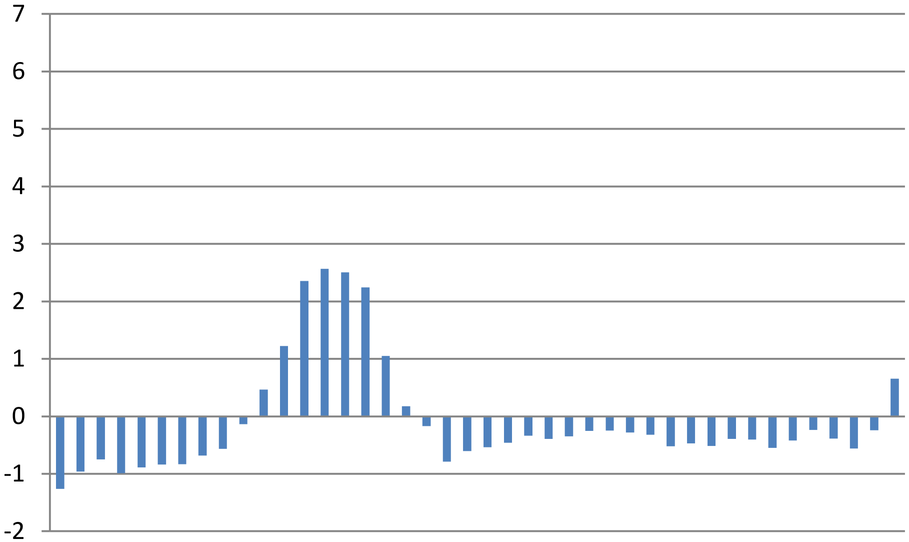


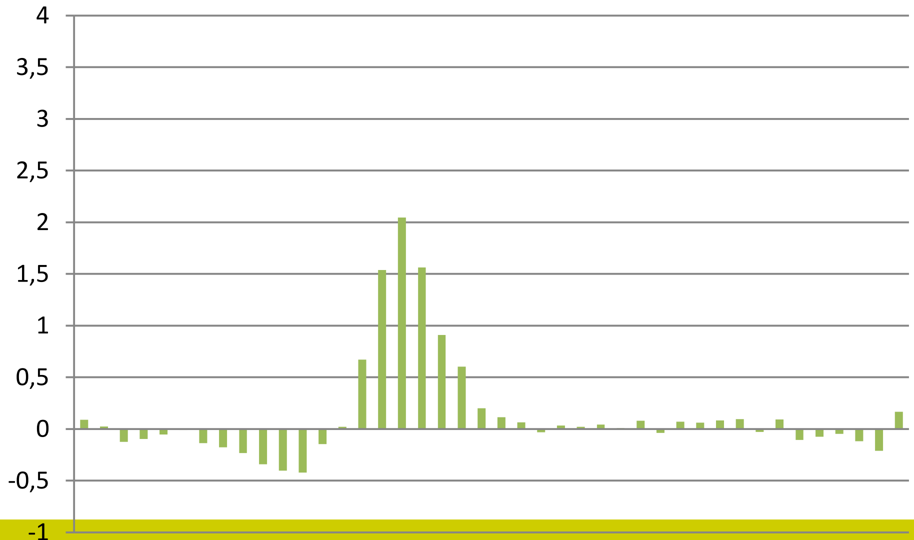
= RoI 5 - Reference RoI

AOI = 43 °

graphene



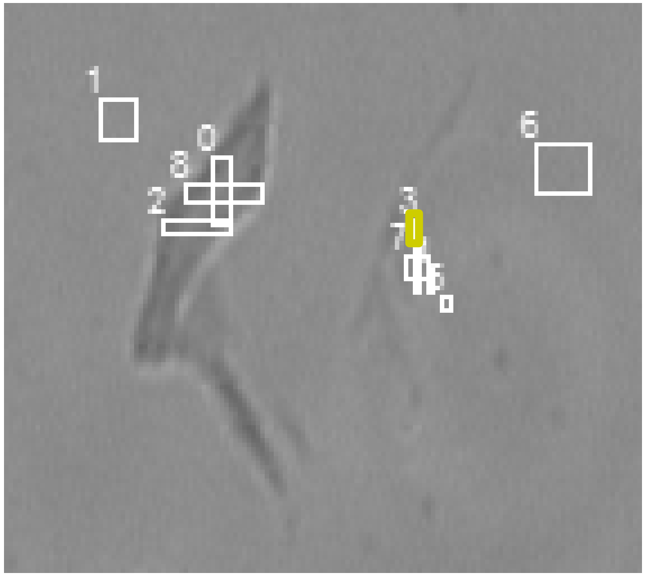


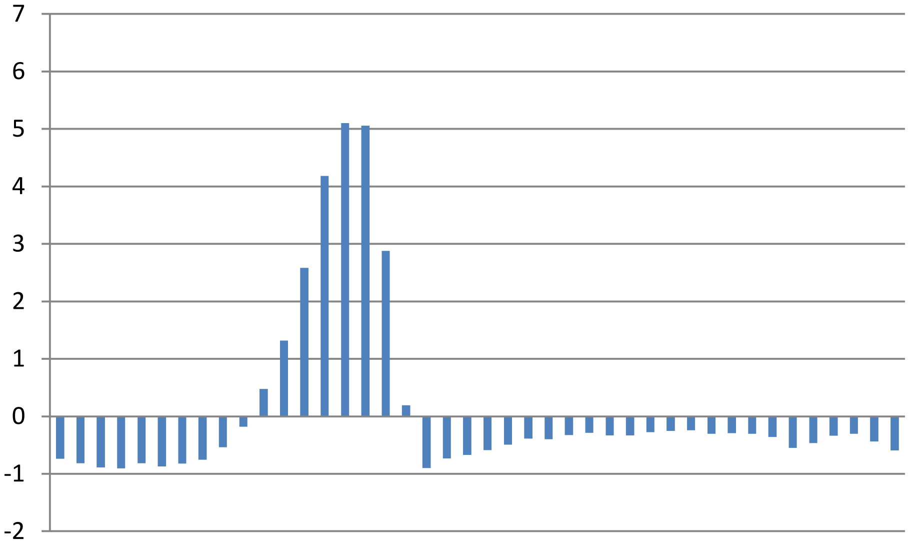


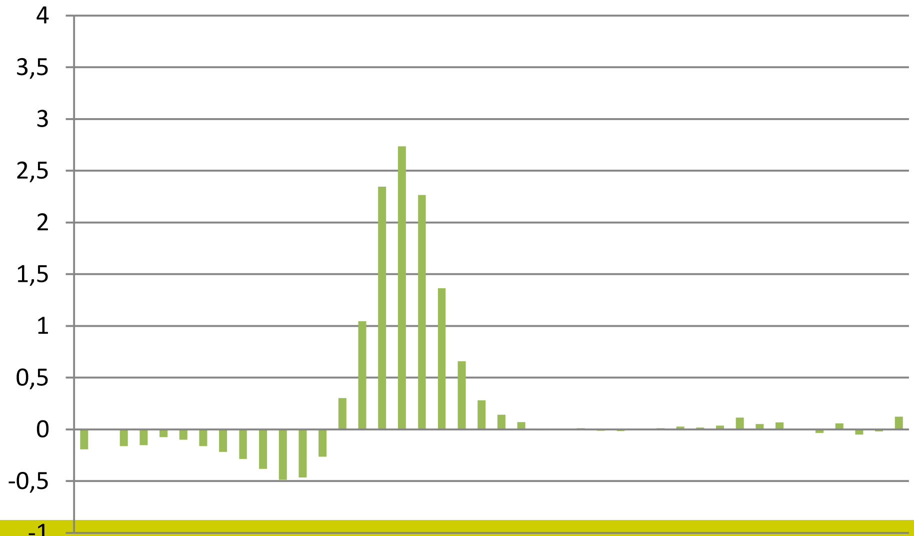
= RoI 3 - Reference RoI

AOI = 43 °

graphene



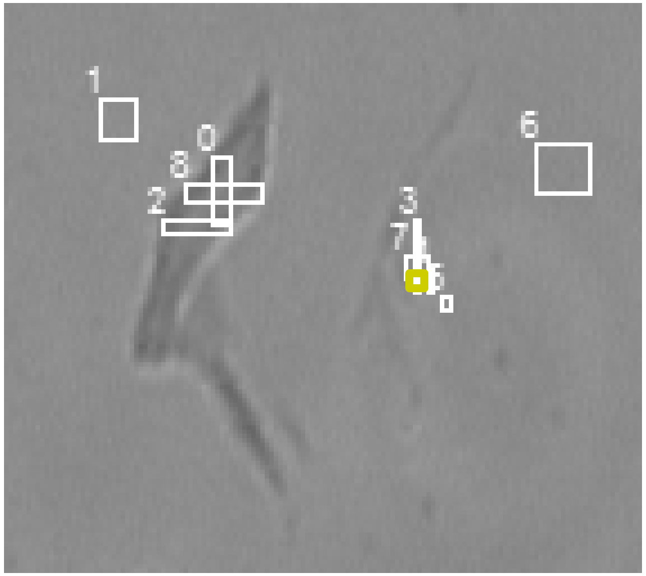


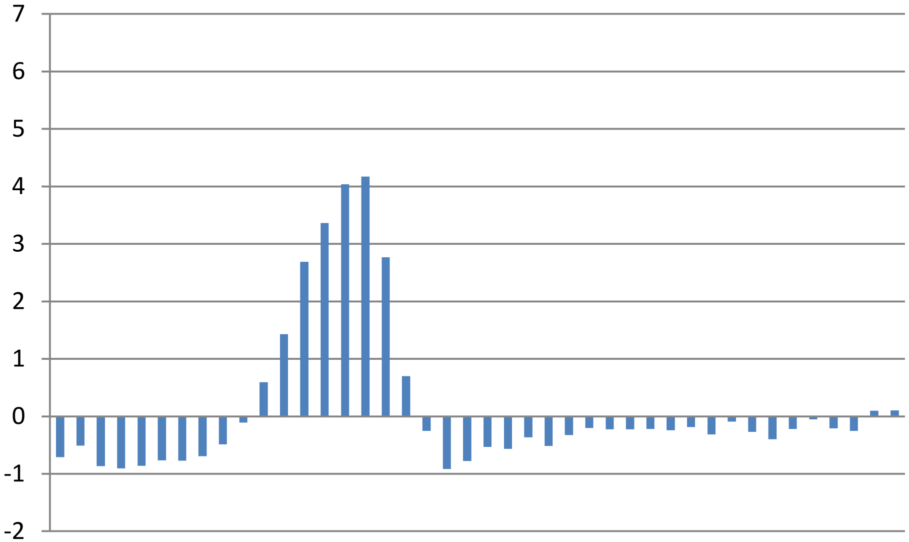


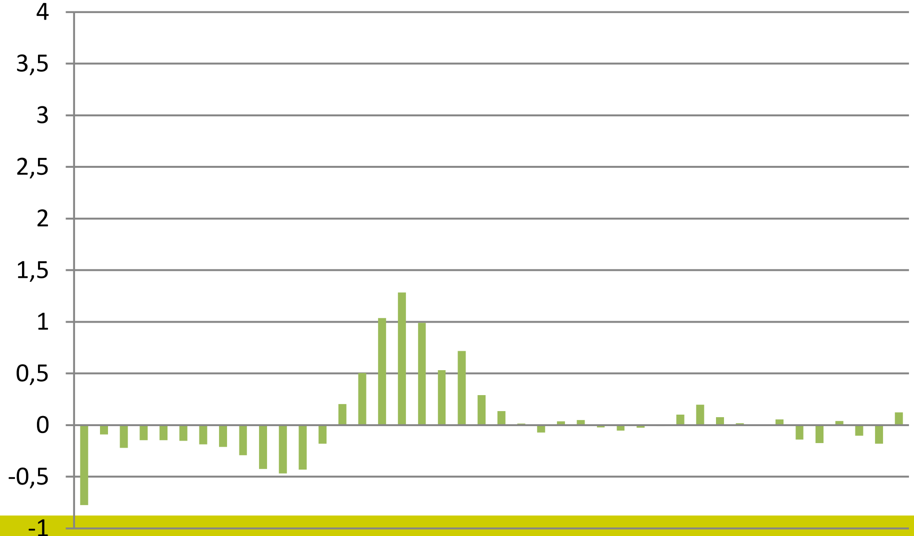
= RoI 4 - Reference RoI

AOI = 43 °

graphene



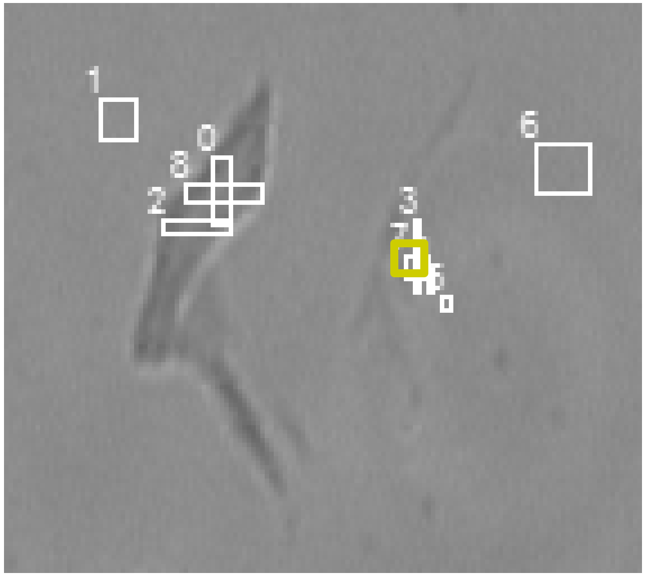


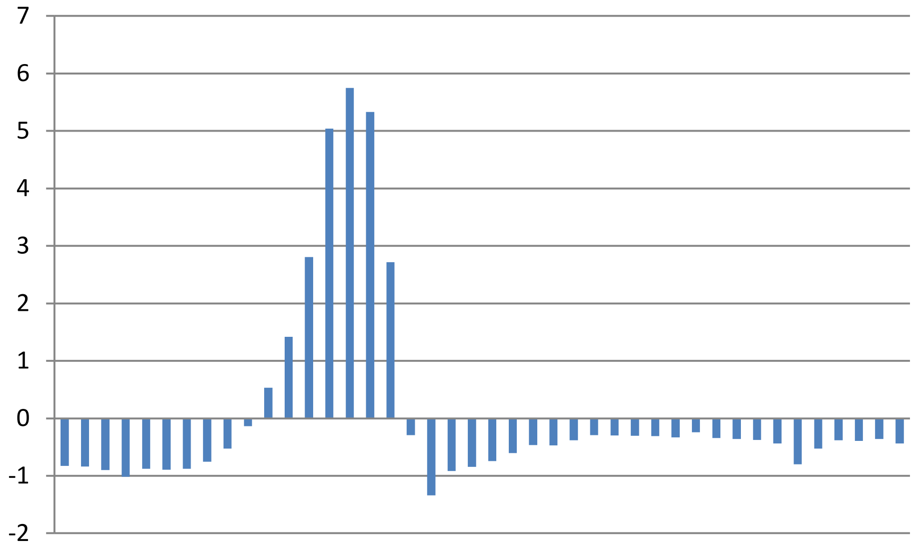


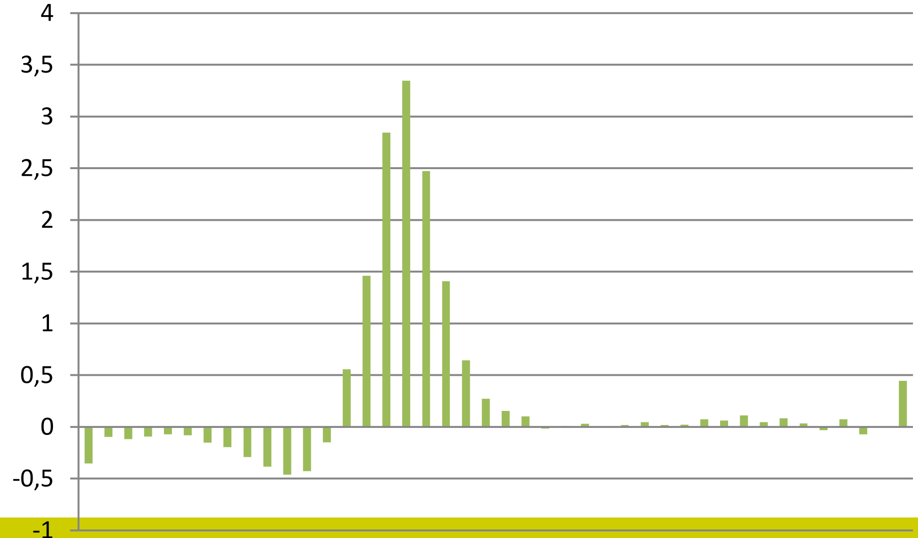
= RoI 7 - Reference RoI

AOI = 43 °

graphene



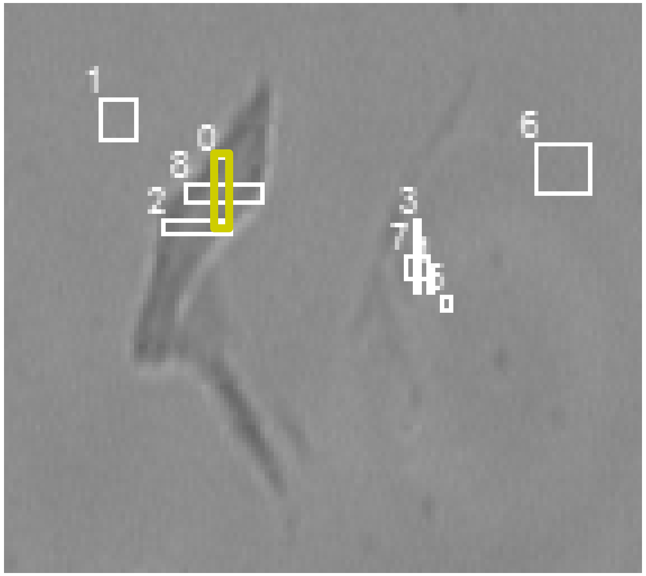


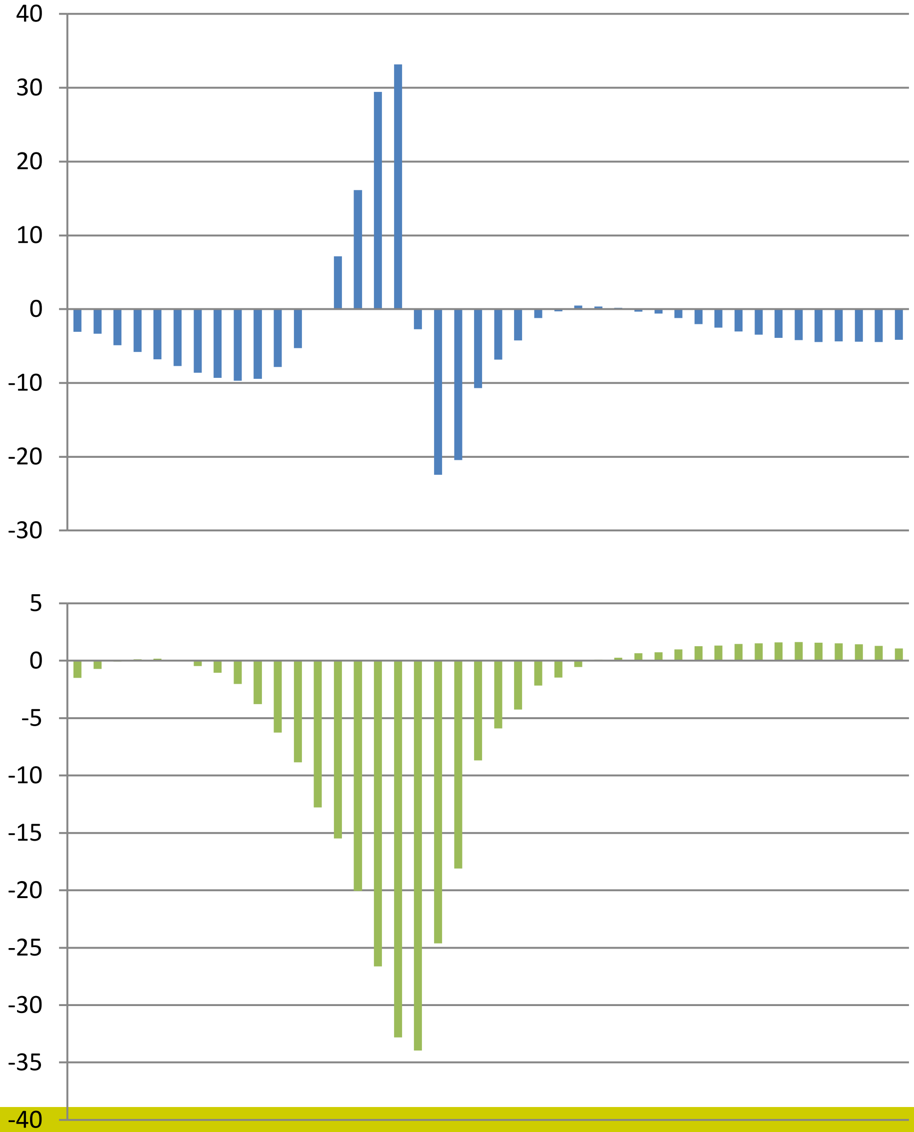


= RoI 0 - Reference RoI

AOI = 43 °

graphite

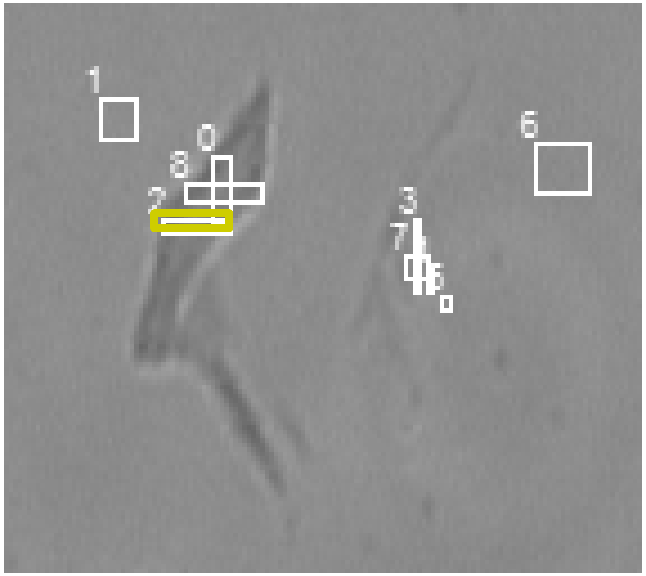


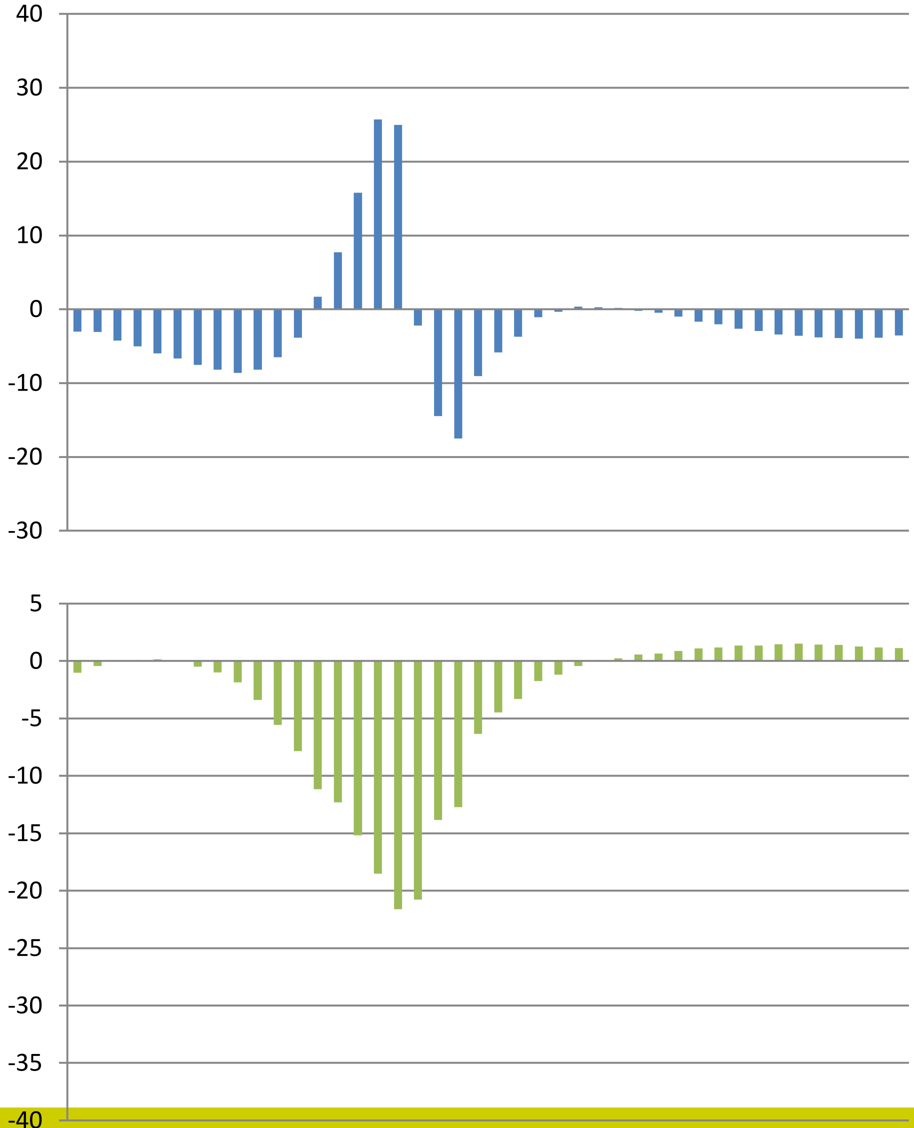


= RoI 2 - Reference RoI

AOI = 43 °

graphite

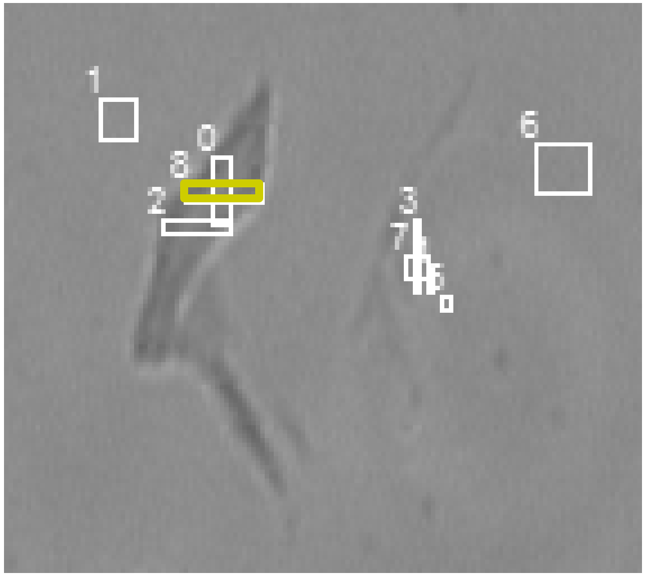


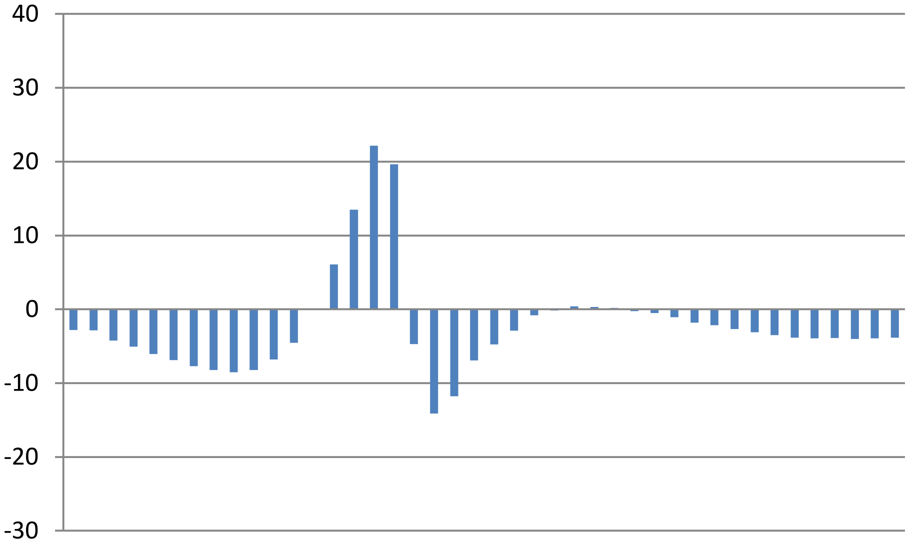


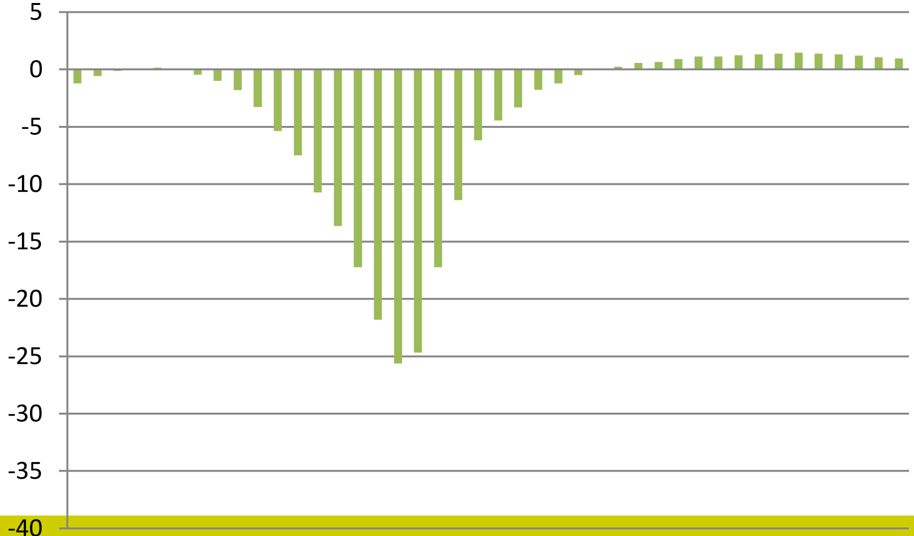
= RoI 8 - Reference RoI

AOI = 43 °

graphite



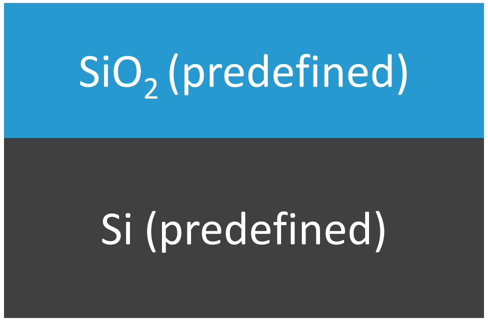


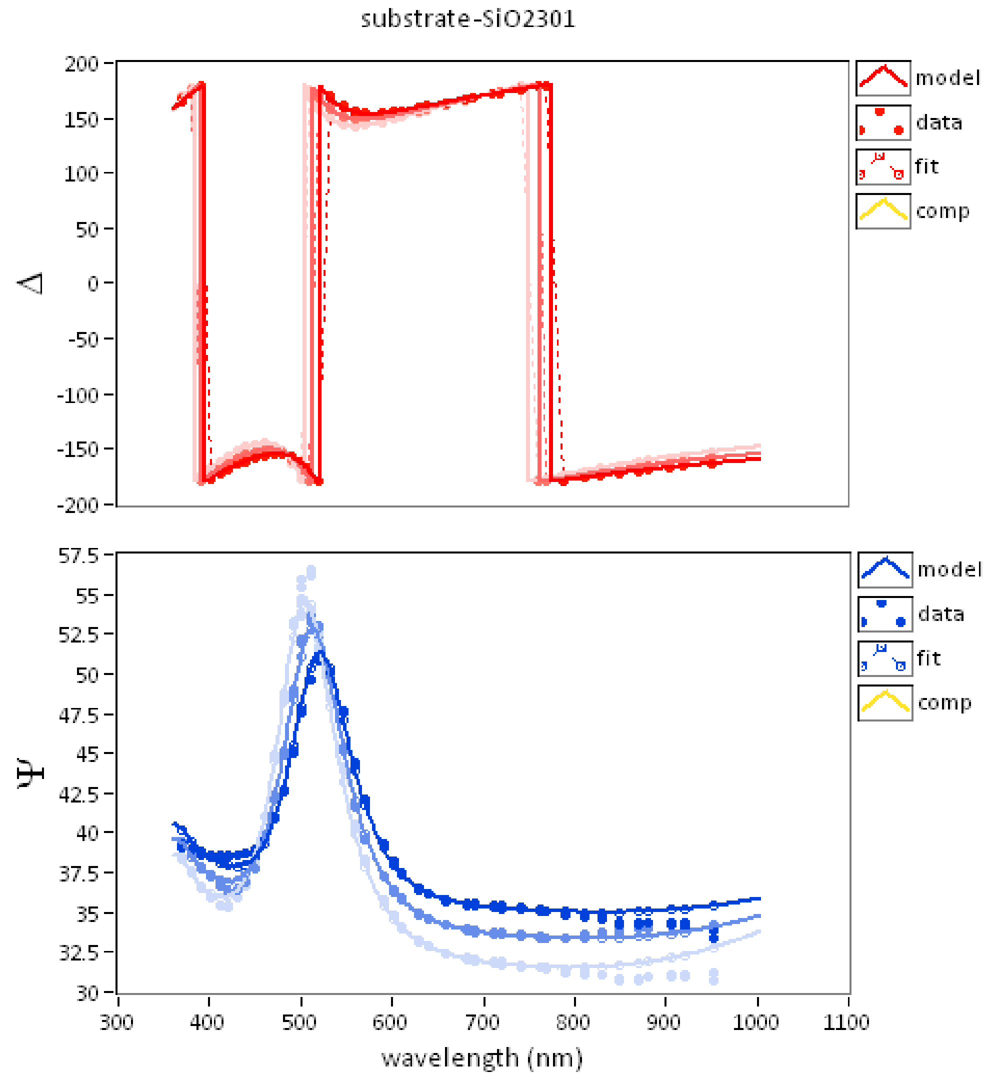


- ellipsometric characterization
    - Optical model

Modeling

1. step: calculation of the SiO_2 thickness





Modeling

1. step: calculation of the SiO_2 thickness

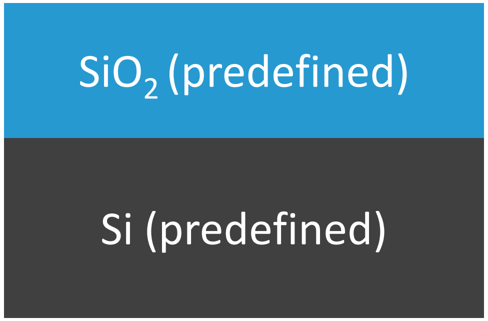
SiO_2 (predefined)

Si (predefined)

ROI	Thickness / nm	RMSE
1	302.0	1.009
6	301.8	1.082

Modeling

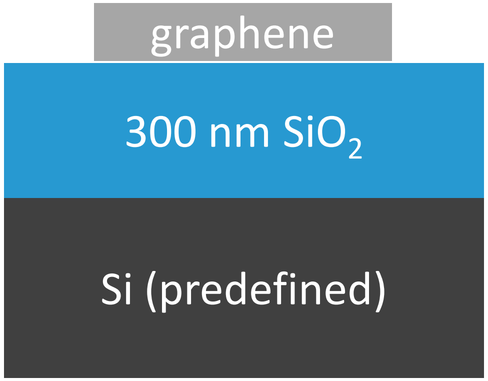
1. step: calculation of the SiO_2 thickness



ROI	Thickness / nm	RMSE
1	302.0	1.009
6	301.8	1.082
1+6	301.9	1.047

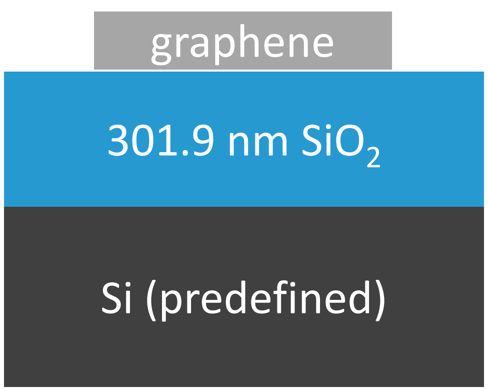
Modeling

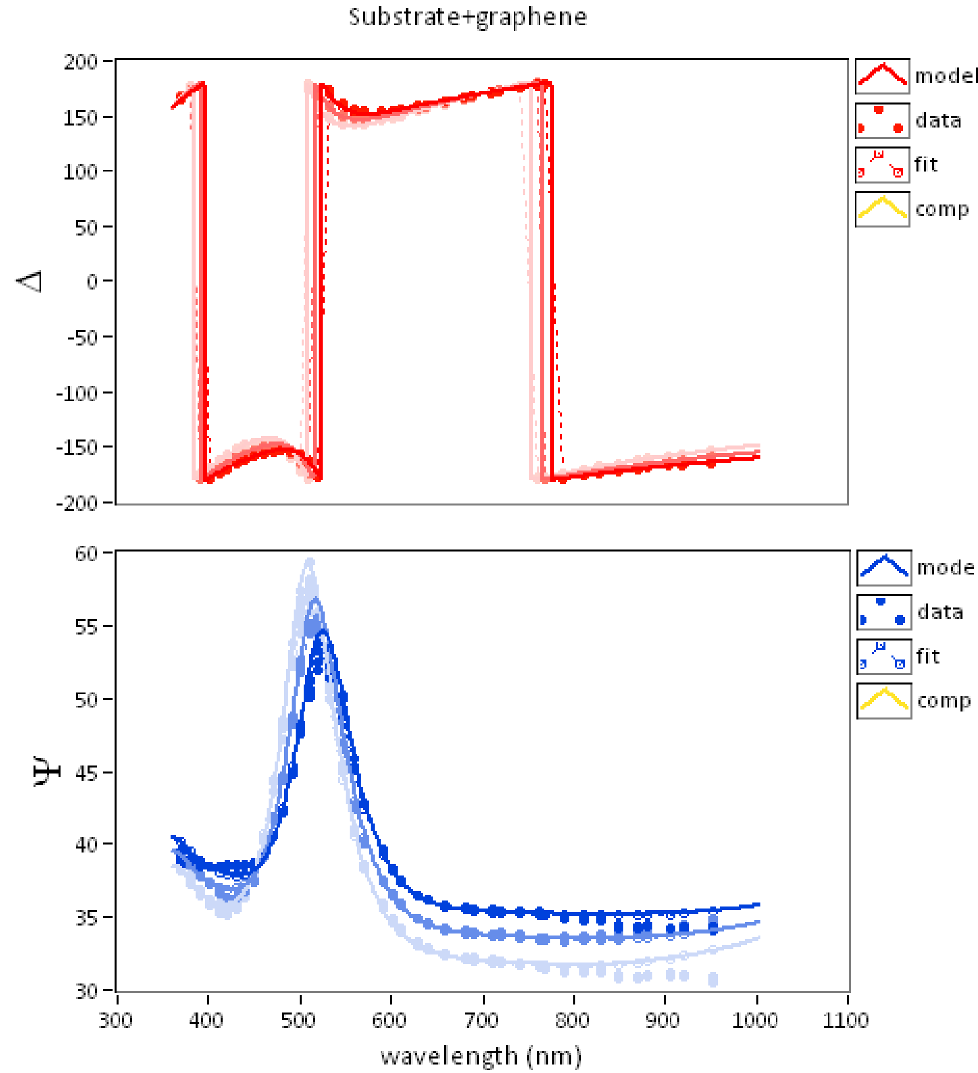
2. step: n and k for graphene from Wang et al. at 532 and 633 nm
-- linear interpolation



Modeling

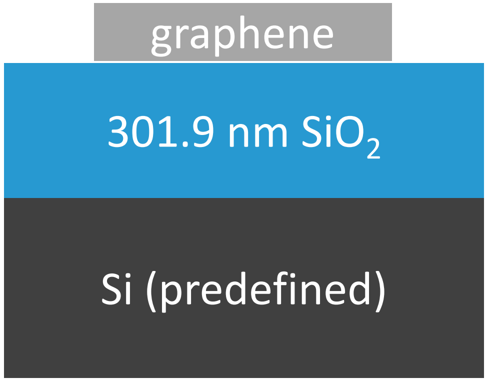
2. step: n and k for graphene from Wang et al. at 532 and 633 nm – linear interpolation





Modeling

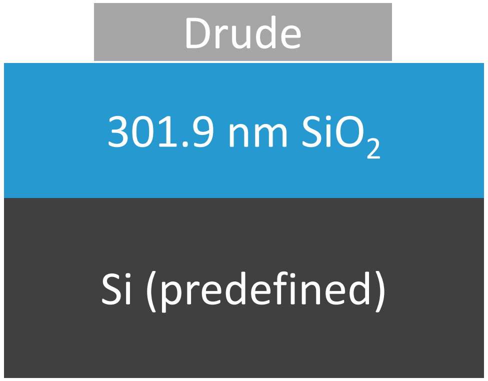
2. step: n and k for graphene from Wang et al. at 532 and 633 nm – linear interpolation



ROI	Thickness / nm	RMSE
3	0.5	1.157
4	0.4	1.152
5	0.5	1.186
7	0.5	1.489

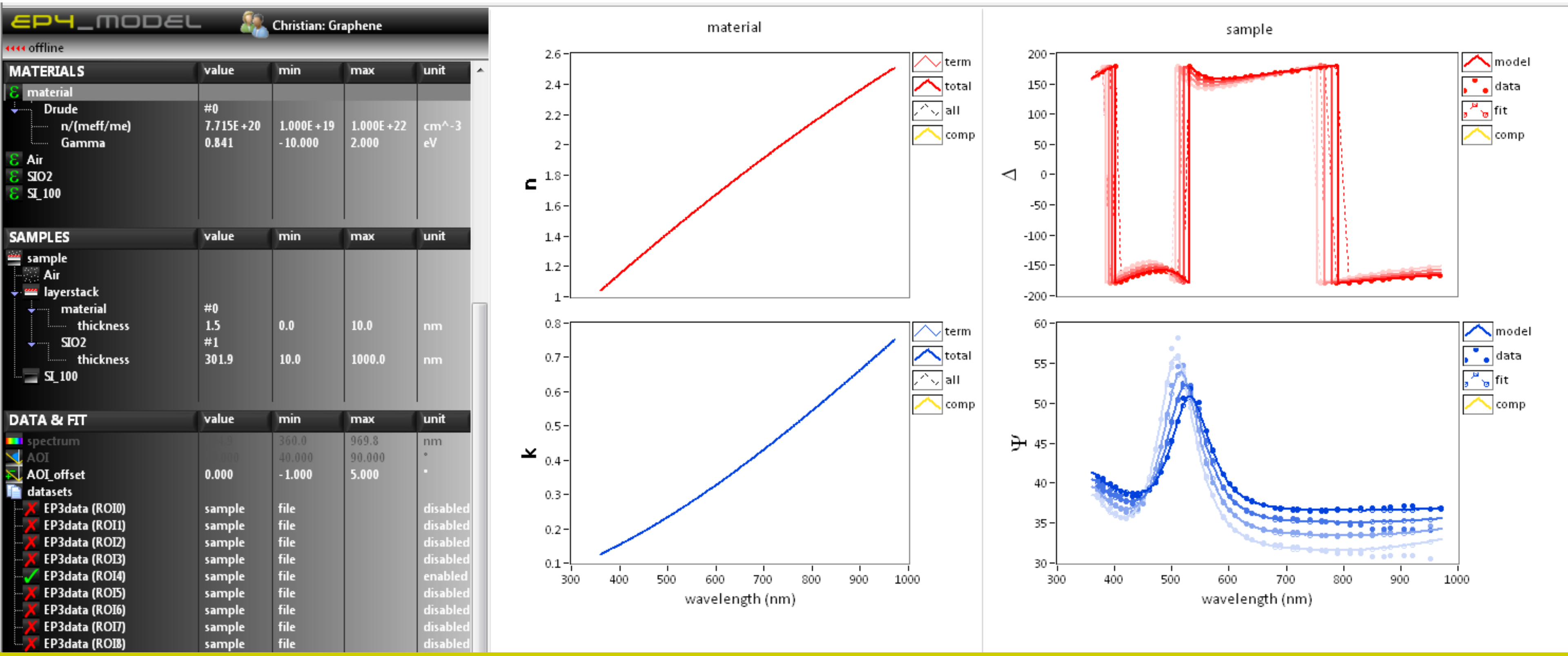
- Modeling

Drude function



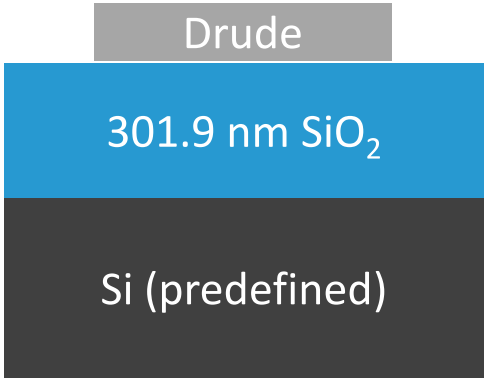
Modeling

Drude function



Modeling

Drude function
Best fit **ROI 3**



results

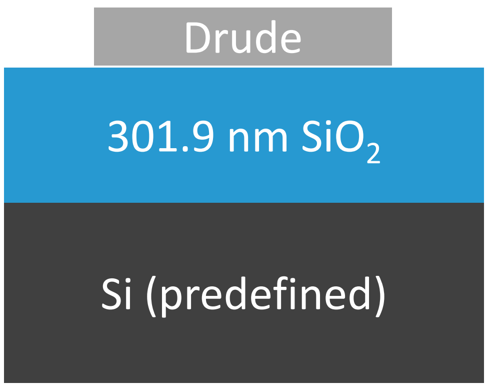
	best fit	+/-	unit
thickness (layer#0 @ Substrate	0.53	0.13	nm
n/(meff/me) (Drude#0 @ mat	2.739E+21	.546E+20	cm^-3
Gamma (Drude#0 @ material_	1.524	0.129	eV
RMSE	0.919		

correlation

	thickness	n/(meff/	Gamma
thickness	1.000	-0.985	-0.444
n/(meff/r	-0.985	1.000	0.523
Gamma	-0.444	0.523	1.000

Modeling

Drude function
Best fit **ROI 4**



results

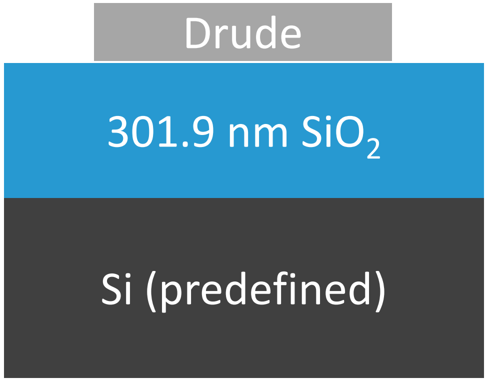
	best fit	+/-	unit
thickness (layer#0 @ Substrate	0.42	0.13	nm
n/(meff/me) (Drude#0 @ mat	2.739E+21	'.920E+20	cm^-3
Gamma (Drude#0 @ material_	1.410	0.147	eV
RMSE	0.875		

correlation

	thicknes:	n/(meff/	Gamma
thickness	1.000	-0.986	-0.423
n/(meff/r	-0.986	1.000	0.497
Gamma	-0.423	0.497	1.000

Modeling

Drude function
Best fit **ROI 5**



results

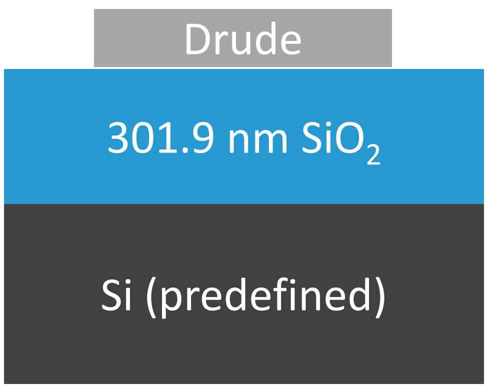
	best fit	+/-	unit
thickness (layer#0 @ Substrate	0.51	0.14	nm
n/(meff/me) (Drude#0 @ mat	2.739E+21	.289E+20	cm^-3
Gamma (Drude#0 @ material_	1.799	0.170	eV
RMSE	0.960		

correlation

	thickness	n/(meff/	Gamma
thickness	1.000	-0.982	-0.487
n/(meff/r	-0.982	1.000	0.579
Gamma	-0.487	0.579	1.000

Modeling

Drude function
Best fit **ROI 7**



results

	best fit	+/-	unit
thickness (layer#0 @ Substrate	0.63	0.13	nm
n/(meff/me) (Drude#0 @ mat	2.739E+21	.601E+20	cm^-3
Gamma (Drude#0 @ material_	1.840	0.132	eV
RMSE	0.914		

correlation

	thickness	n/(meff/	Gamma
thickness	1.000	-0.982	-0.494
n/(meff/r	-0.982	1.000	0.587
Gamma	-0.494	0.587	1.000

Modeling

Drude function
Best fit **ROI 7**

results

	best fit	+/-	unit
thickness (layer#0 @ Substrate	0.63	0.13	nm
n/(meff/me) (Drude#0 @ mat	2.739E+21	.601E+20	cm^-3
Gamma (Drude#0 @ material_	1.840	0.132	eV
RMSE	0.914		

High correlation between thickness and (n/meff)

$\Rightarrow$ with additional information concerning the thickness, the dispersion function is available.

correlation

	thicknes	n/(meff/	Gamma
thickness	1.000	-0.982	-0.494
n/(meff/r	-0.982	1.000	0.587
Gamma	-0.494	0.587	1.000