Light for the nanoworld – Overview of applications with plasma based extreme ultraviolet sources

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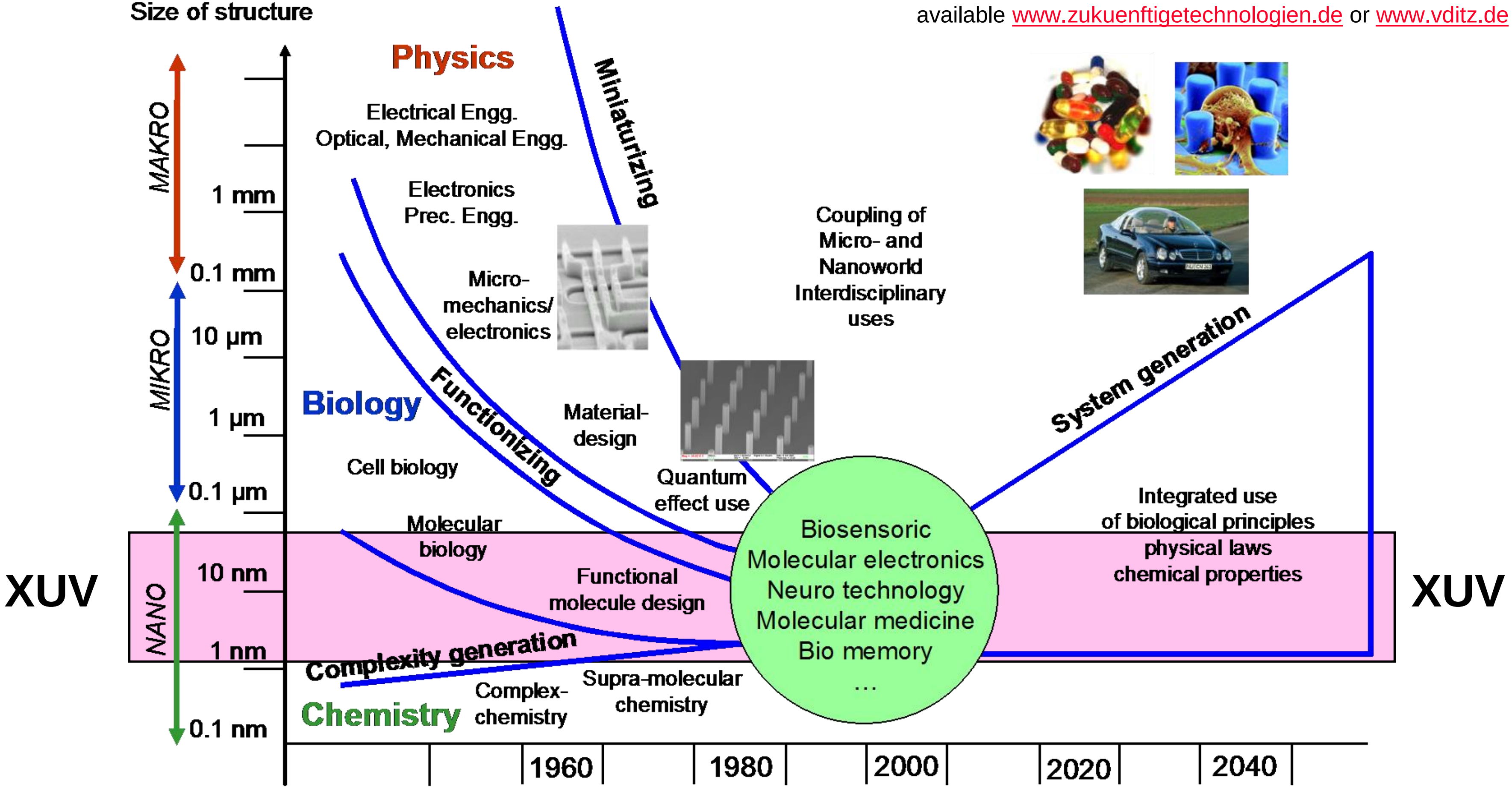
EXPERIMENTAL PHYSICS
OF EXTREME ULTRAVIOLET

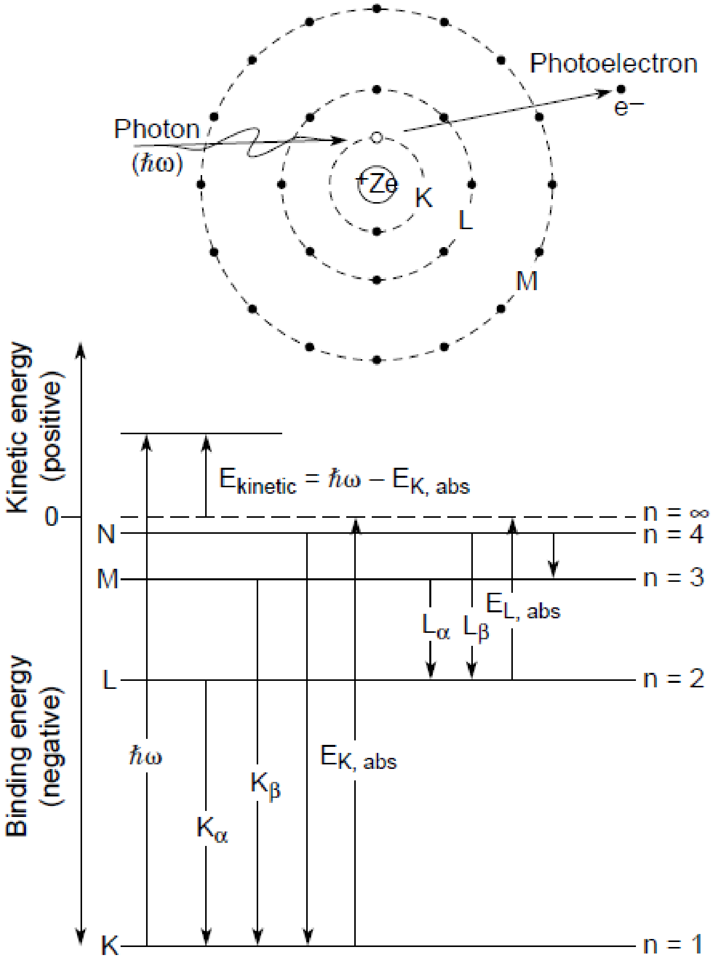
JARA|FIT
Fundamentals of Future
Information Technology

Nanotechnology

from: A. Zweck, Nanotechnologie: Technologiefrüherkennung, Innovationsmanagement und Perspektiven, (2006) available www.zukuenftigetechnologien.de or www.vditz.de



Binding energies



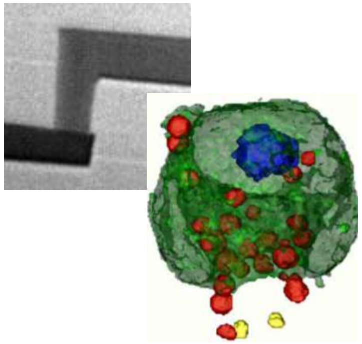
Element	K1s	L$_1$2s	L$_2$2p$_{1/2}$	L$_3$2p$_{3/2}$	M$_1$3s	M$_2$3p$_{1/2}$	M$_3$3p$_{3/2}$	M$_4$3d$_{3/2}$	M$_5$3d$_{5/2}$	N$_1$4s
1 H	13.6									
2 He	24.6									
6 C	284.2									
7 N	409.9	37.3								
8 O	543.1	41.6								
13 Al	1559.6	117.8	72.9	72.5						
14 Si	1838.9	149.7	99.8	99.2						
16 S	2472	230.9	163.6	162.5						
20 Ca	4038.5	438.4	349.7	346.2	44.3	25.4	25.4			
22 Ti	4966.4	560.9	461.2	453.8	58.7	32.6	32.6			
24 Cr	5989.2	695.7	583.8	574.1	74.1	42.2	42.2			
26 Fe	7112.0	844.6	719.9	706.8	91.3	52.7	52.7			
27 Co	7708.9	925.1	793.3	778.1	101.0	58.9	58.9			
28 Ni	8332.8	1008.6	870.0	852.7	110.8	68.0	66.2			
29 Cu	8978.9	1096.7	952.3	932.5	122.5	77.3	75.1			
30 Zn	9658.6	1196.2	1044.9	1021.8	139.8	91.4	88.6	10.2	10.1	
42 Mo	19999.5	2865.5	2625.1	2520.2	506.3	411.6	394.0	231.1	227.9	63.2
47 Ag	25514.0	3805.8	3523.7	3351.1	719.0	603.8	573.0	374.0	368.0	97.0
54 Xe	34561.4	5452.8	5103.7	4782.2	1148.7	1002.1	940.6	689.0	676.4	213.2
79 Au	80724.9	14352.8	13733.6	11918.7	3424.9	3147.8	2743.0	2291.1	2205.7	762.1

EUV, λ ~ 5 – 50 nm

SXR, λ ~ 1 – 5 nm

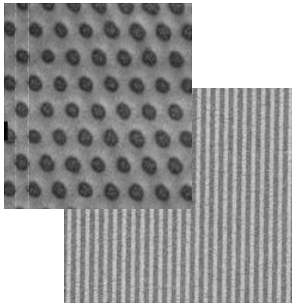
Applications summary

XUV: short wavelength and strong light matter interaction → lateral & in-depth (3d) nm resolutions with element sensitivity and high throughput



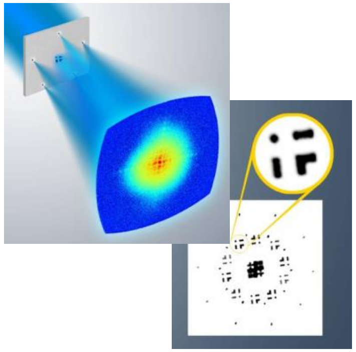
Microscopy

- 3d imaging (cells, electronics)
- “no” sample preparation
- several µm penetration depths
- magnetic (spin) contrast with polarized light



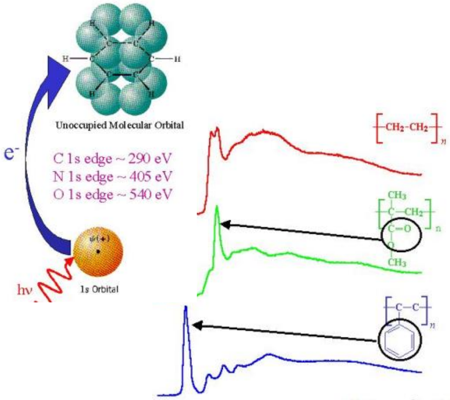
Patterning

- high density arrays
- large exposition areas
- access to < 10 nm scale
- negligible proximity effect
- independent on substrate



Scatter/diffractometry

- nano-roughness
- nano-structures arrays
- nano-defect inspection
- lens less imaging with coherent light



Spectroscopies

- element selectivity
- chemical bonding (NEXAFS)
- small penetration depths of radiation (<100 nm)
- large grazing incidence angle

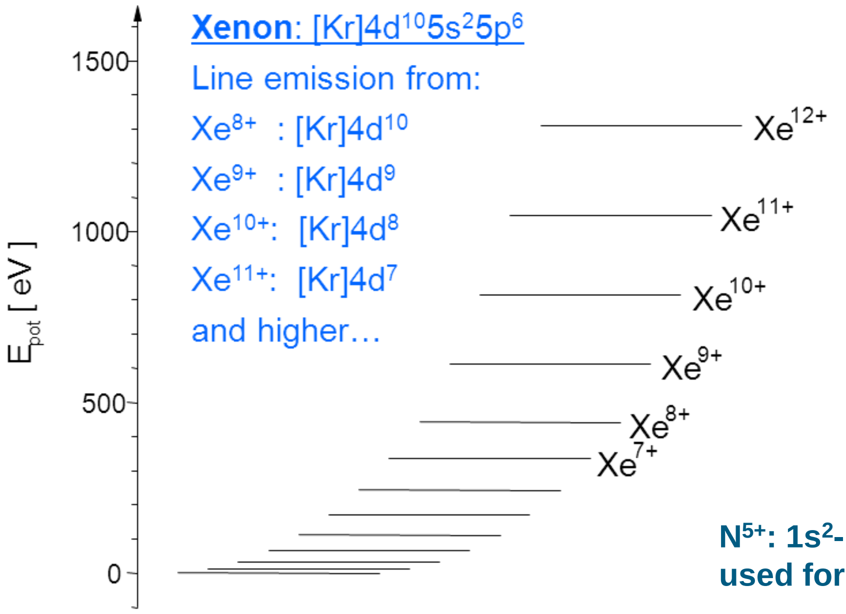
Radiation sources

- Synchrotron radiation (bending magnet, wiggler, undulator)
- X-ray tubes (e.g. Si L-edge at 100 eV)
- High Harmonic Generation
- Plasma based radiation sources

1% x-ray, 99% heat due to infrared transitions of excited outer-shell electrons

highly ionized ions with outer-shell transitions in XUV (up to 90%)

$$P_{radiation} = P_{line} + P_{recombination} + P_{bremsstrahlung}$$



Xenon: [Kr]$4d^{10}5s^{2}5p^{6}$

Line emission from:

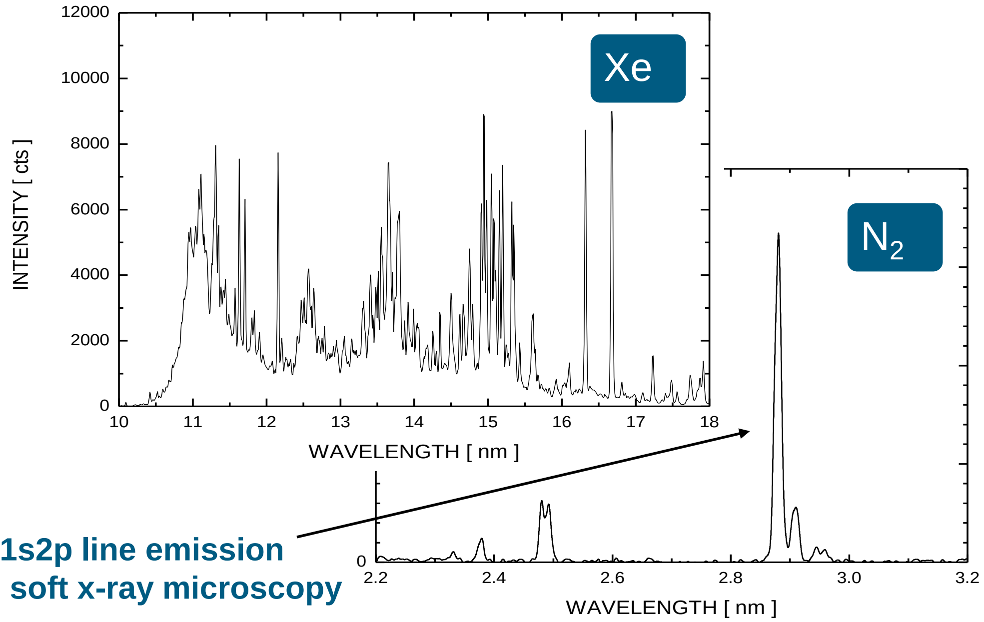
Xe^{8+} : [Kr]$4d^{10}$

Xe^{9+} : [Kr]$4d^{9}$

Xe^{10+}: [Kr]$4d^{8}$

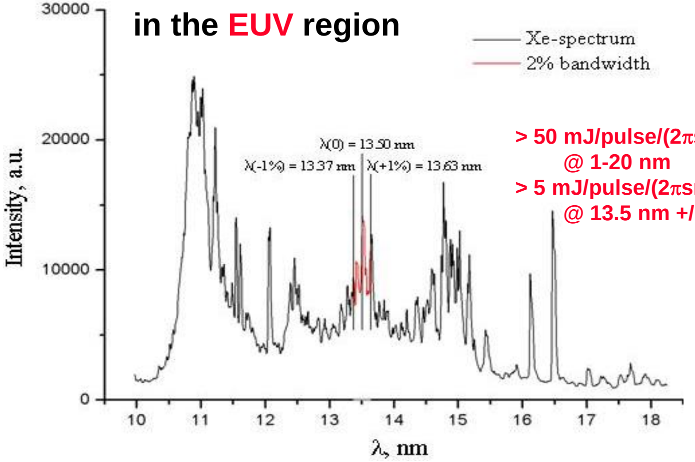
Xe^{11+}: [Kr]$4d^{7}$

and higher…

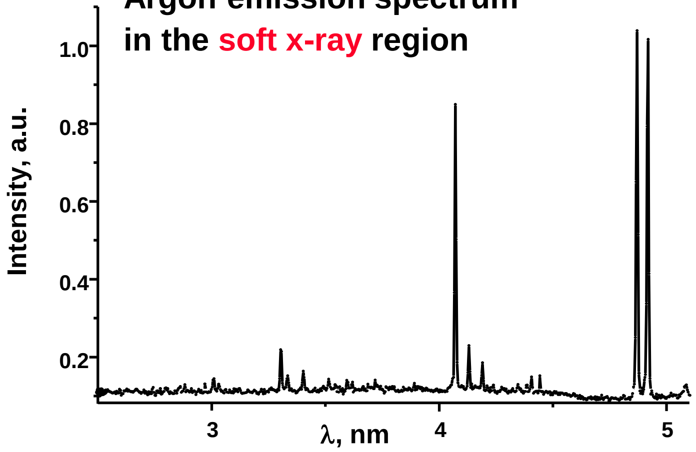


N^{5+}: $1s^2$-1s2p line emission used for soft x-ray microscopy

Laboratory scale plasma-based XUV sources


Xenon emission spectrum in the EUV region

> 50 mJ/pulse/(2πsr) @ 1-20 nm
> 5 mJ/pulse/(2πsr) @ 13.5 nm +/-2 %


Argon emission spectrum in the soft x-ray region

basic physics:

- emission spectrum consists of single lines or bunch of lines (UTA, quasi-continuum) of high ionized ions depending on plasma parameters, composition and dynamics
- XUV lasers exist - more sophisticated to achieve plasma parameters
- emission always pulsed, max. few 100 ns

technological aspects

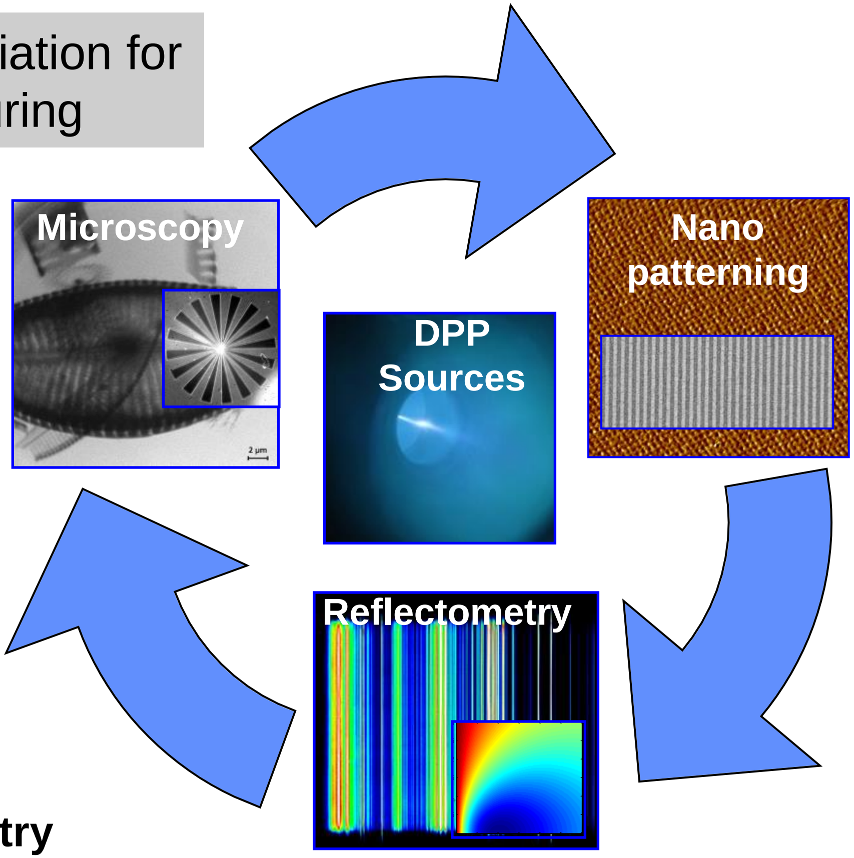
- LPP and DPP with main differences in diameter and pulse duration
- large technological progress within the last decade due to EUV lithography (up to 800W/2πsr @ 13.5 nm in 2% bw)
- commercial sources already available
- impact on laboratory scale applications

Research Activities of EUV Technology Group at RWTH/ILT

Utilization of EUV radiation for metrology and structuring

Microscopy
- Defect detection
- EUV mask inspection
- Water window microscopy (ILT)

see smaller features



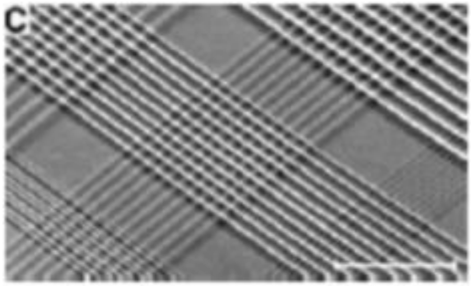
Lithography
- Nanostructuring of surfaces with laboratory sources
- Patterning of structures < 10 nm

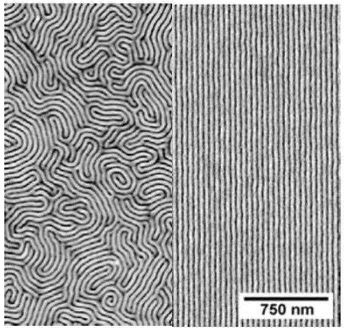
write smaller patterns

Reflectometry
- Analysis of nanolayers and surfaces
- Layer thickness and roughness measurement
- Elemental composition

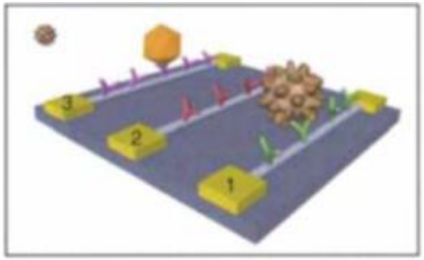
analyze with elemental and chemical sensitivity

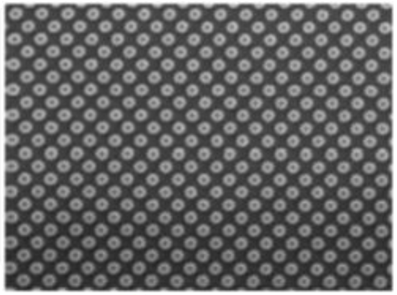
Nano-structuring - Motivation





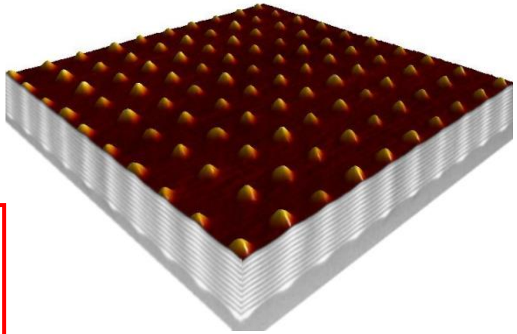
There is a strong demand for lab-scale EUV IL setup for creation of dense periodic patterns over large area with sub-20 nm resolution.





Applications:

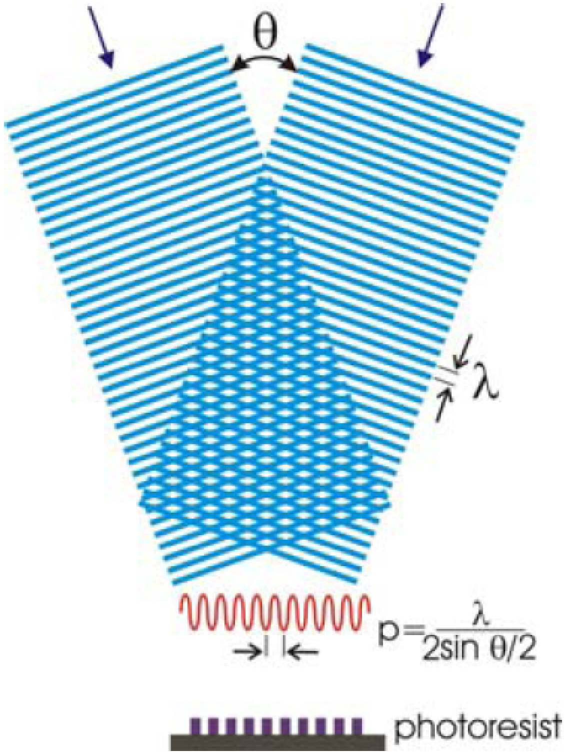
- templates for guided self-assembly
- nano-optics, meta-materials
- ultra high density patterned magnetic media
- quantum dot 2D and 3D arrays, nanowire arrays



Successfully used with synchrotron radiation =>

Enabling technology, if achieved with laboratory sources

Interference lithography

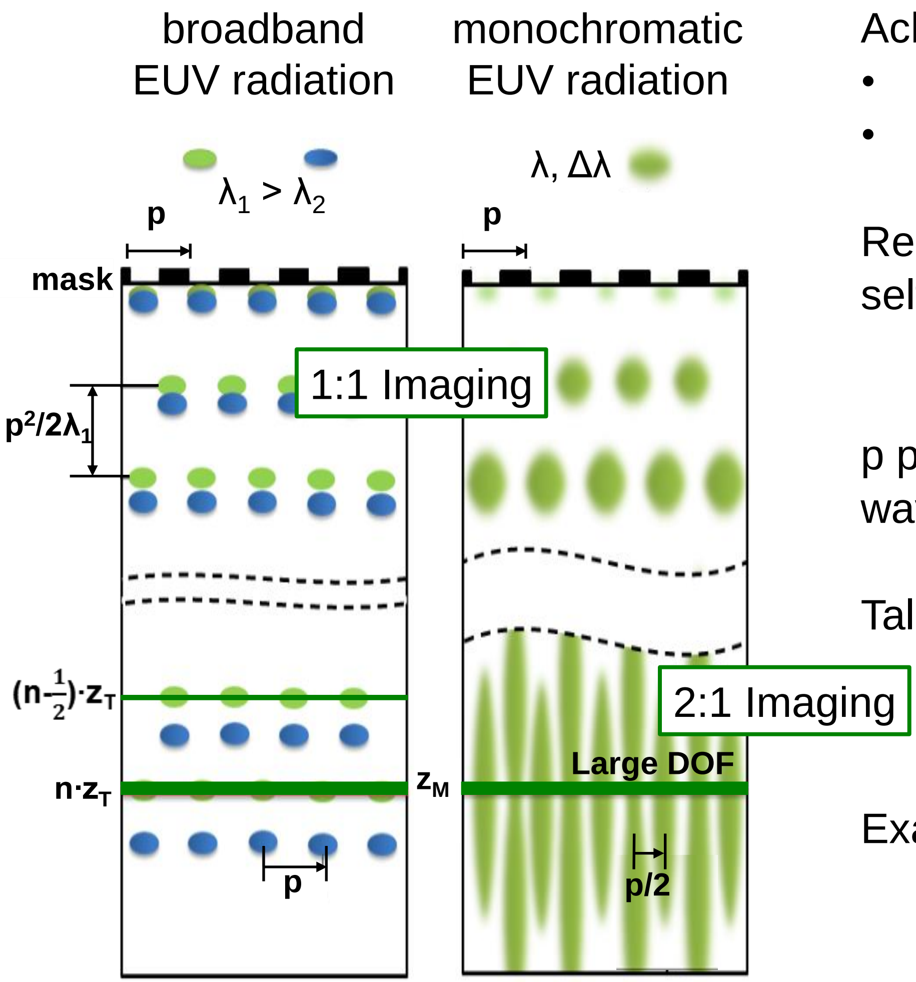


- Large-area periodic structures
- Large depth of focus
- Requires a coherent light
- Low cost – no complicated and expensive optics
- Ultimate resolution (half-pitch) for the wavelength ~λ/4

EUV: λ = 11 nm ➡ feature size: ~3 nm

EUV-IL: high resolution, scalable throughput, simple optical system, negligible proximity effect, no charging effects

Talbot self-imaging, 2:1 pattern demagnification



Achromatic Talbot self-imaging:

- Demagnification of pattern by up to a factor of 2
- Large depth of field

Required spatial coherence for achromatic Talbot self-imaging:

$$l_{coh}=4p\lambda/\Delta\lambda$$

p period for l/s or pinhole grating, λ illumination wavelength, $\Delta\lambda$ bandwidth of radiation

Talbot distance:

monochromatic: $n\cdot Z_T=2p^2/\lambda$
achromatic: $Z_M=2p^2/\Delta\lambda$

Example: $n=1$, $p=100$ nm, $\lambda=10.9$ nm, $\Delta\lambda/\lambda=3.2\%$
monochromatic: $Z_T=1.83$ µm
achromatic: $Z_M=57.33$ µm

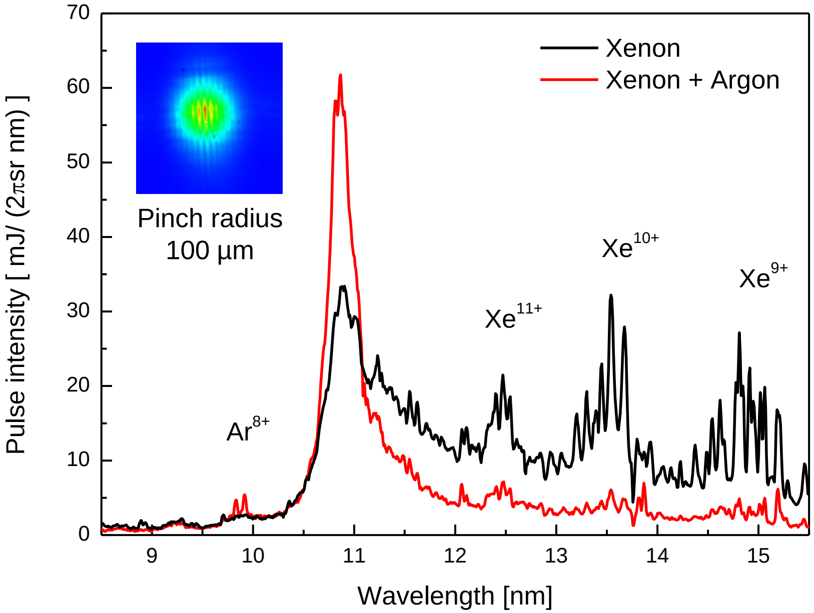
Compact 2kHz EUV source developed at FhG-ILT

100W/(mm^2sr) radiance @ 10.9 nm

Input power 5.6 kW

Source emission optimized to achieve highest possible intensity within necessary bandwidth

K. Bergmann, S.V. Danylyuk, L. Juschkin, J. Appl. Phys. 106, 073309, (2009)



Admixture of Ar to Xe plasma allows to supress 12 - 16 nm lines resulting in radiation at 10.9 nm with 3.2% bw

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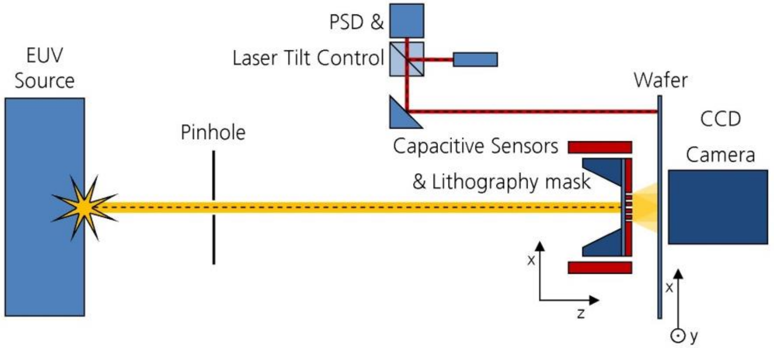
EUV laboratory exposure tool – technical specifications



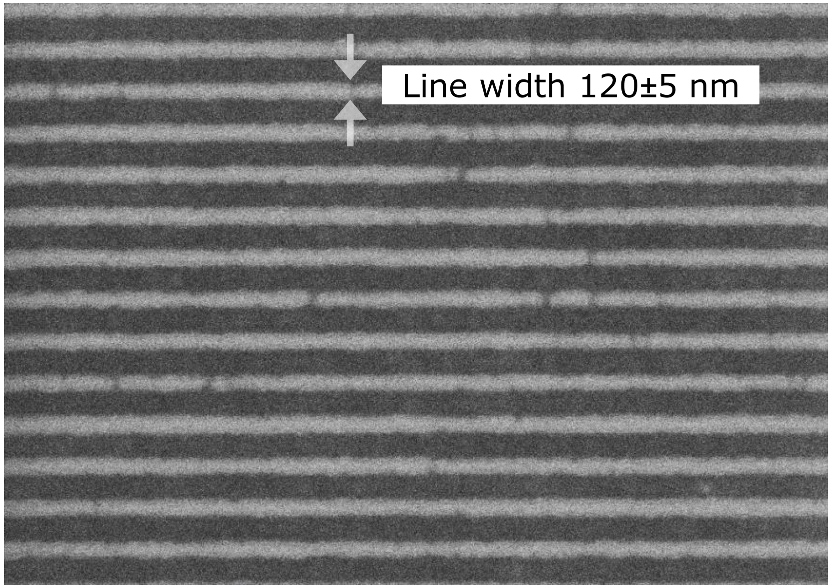
S. Brose, S. Danylyuk, L. Juschkin, D. Grützmacher *et al*, Thin Solid Films 520, 5080 (2012)

- Cleanroom class 100 (ISO 3) environment
- High power EUV discharge produced plasma source:
  - → Optimized emission spectrum with a peak wavelength at λ = 10.9 nm and a spectral bandwidth of 3.2%
  - → Up to 100 W/(mm^{2}sr) radiance at 10.9 nm
- Illumination schemes: proximity printing and Talbot interference lithography
- Accepts up to 100 mm wafer
- Max. exposable area: 65 x 65 mm^2
- Single field: 2 x 2 mm^2
- EUV sensitive CCD camera
- High precision positioners on all axes (encoder resolution < 10 nm)
- Dose monitor for λ = 13.5 nm

Exposure results EUV-LET

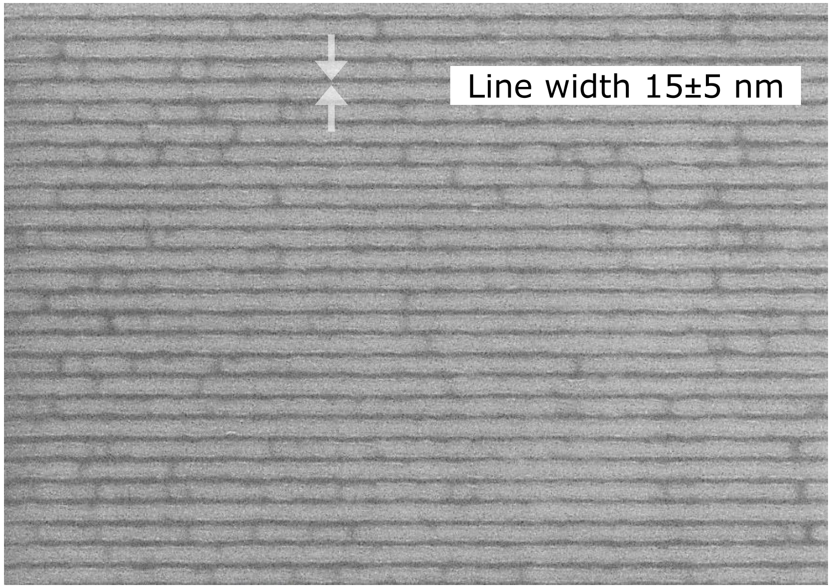
Lines and spaces pattern (half-pitch 100/50 nm)

Proximity printing
Half-pitch 100 nm, distance z ≈ 0 µm
Resist:ZEP520A



→ Same lithography mask
→ Pitch reduced by factor 2
→ Line width reduced by factor ~10

Achromatic Talbot Self-Image
Half-pitch 50 nm, distance z ≈ 50 µm
Resist:ZEP520A

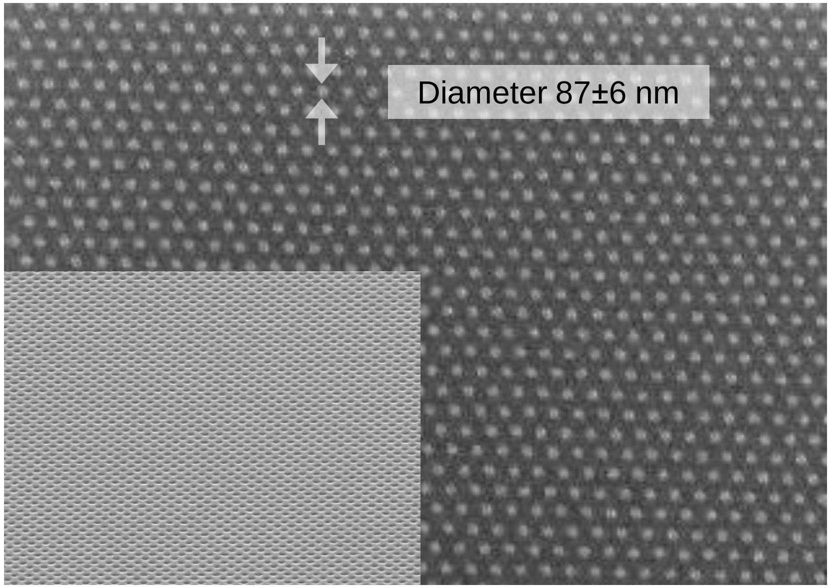


Exemplary application – cross-bar arrays for phase change memory (PCRAM)

Exposure results EUV-LET

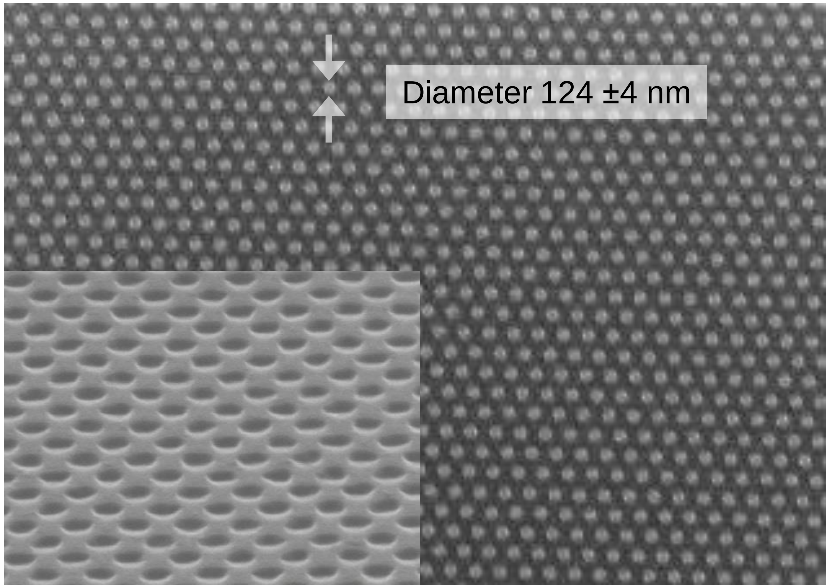
Hexagonal pinhole pattern (half-pitch 100 nm)

Proximity printing
Half-pitch 100 nm, distance z ≈ 0 µm
Resist: SX AR-P 6200 – 02 (CSAR62)



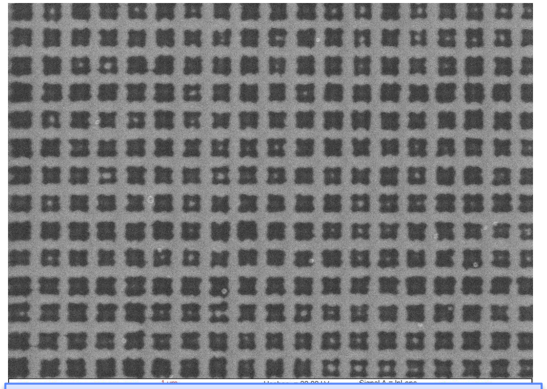
→ Same lithography mask
→ Excellent uniformity
→ Large area exposures

Proximity Printing
Half-pitch 100 nm, distance z ≈ 0 µm
Resist: SX AR-P 6200 – 02 (CSAR62)



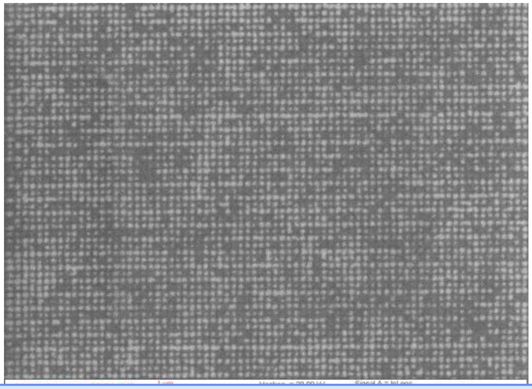
Exemplary application - pre-patterns for self-assembly of quantum dots (QD)

Applications



SFB 917
Nanoswitches

cross-bar arrays for PCRAM



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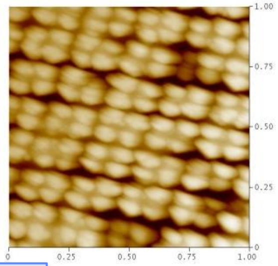
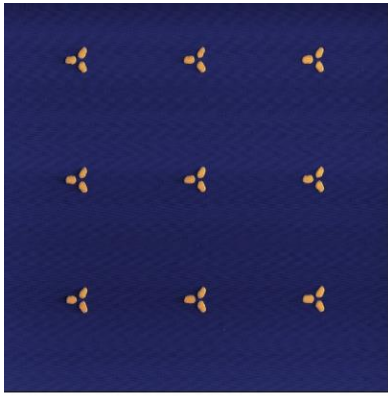
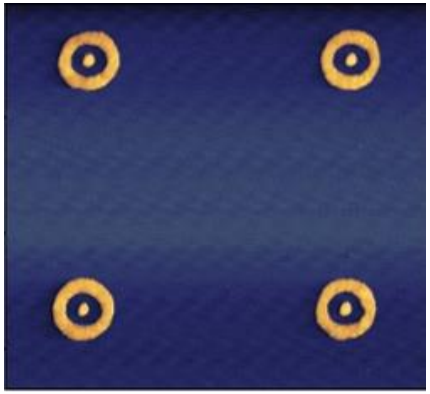
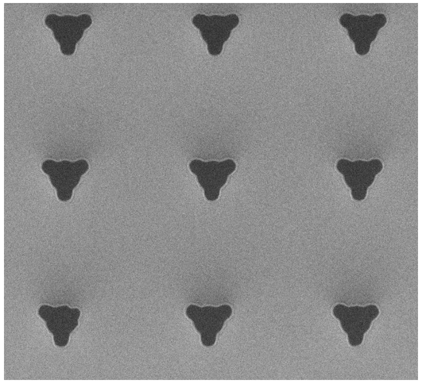


nanodot-arrays for QD self assembly





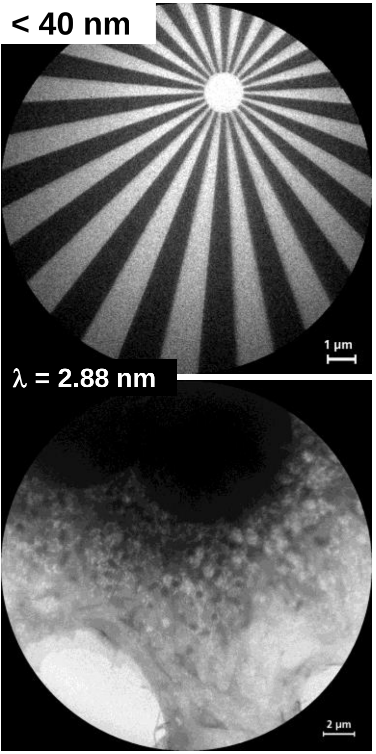


Nanophotonic resonators

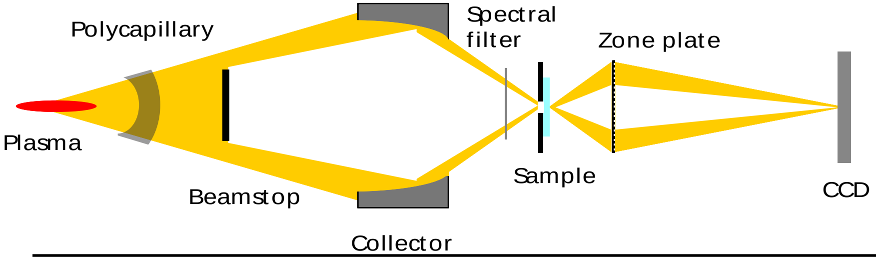
Thermoelectrics -> see presentation
of Mikheil Mebonia, Thursday, P9

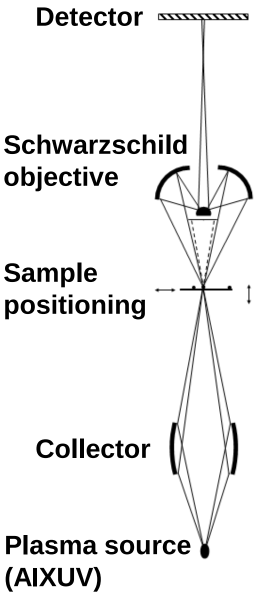
XUV-Microscopy at ILT / TOS

Resolution < 40 nm



λ = 2.88 nm





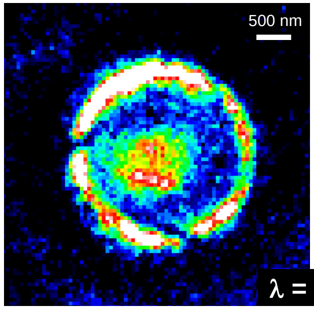
Detector

Schwarzschild objective

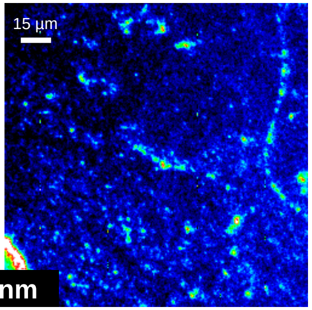
Sample positioning

Collector

Plasma source (AIXUV)



Three 100 nm dots of transmission mask



λ = 13,5 nm

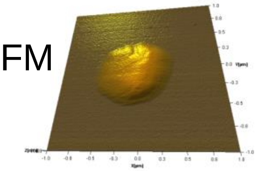
Dark field image of nanoparticles D=112 nm

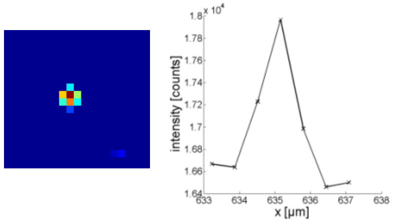
Mask blank inspection

- **Fundamental investigations on defect detection (influence of different kind of defects onto signal)**
- **Fast scanning of large surfaces – with 1 µm resolution and 10 nm sensitivity**
- **Design rules for an industrial mask blank inspection tool (source, optical system, detector, interaction of EUV radiation with a defect)**

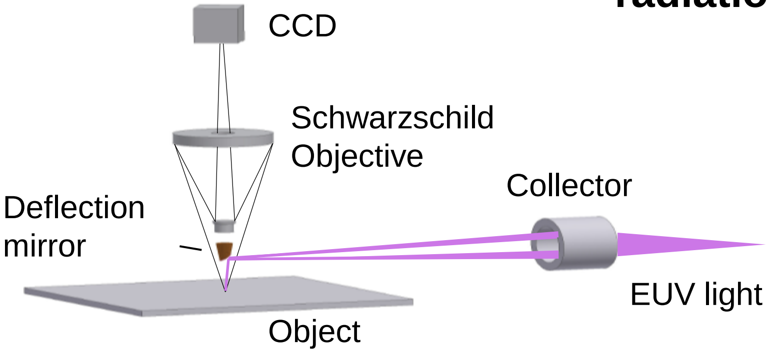
Natural defect:

AFM

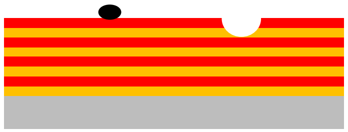


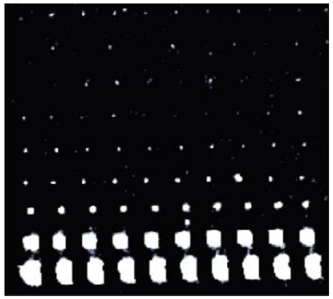


EUV - microscope



Structured bumps:



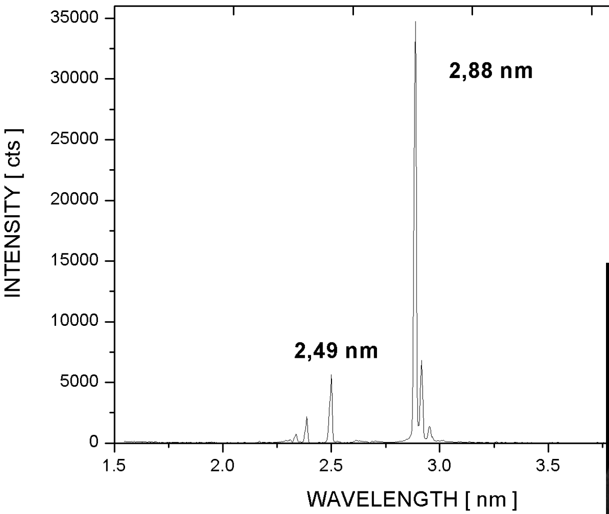


XUV microscopy: soft x-ray microscopy (water window)

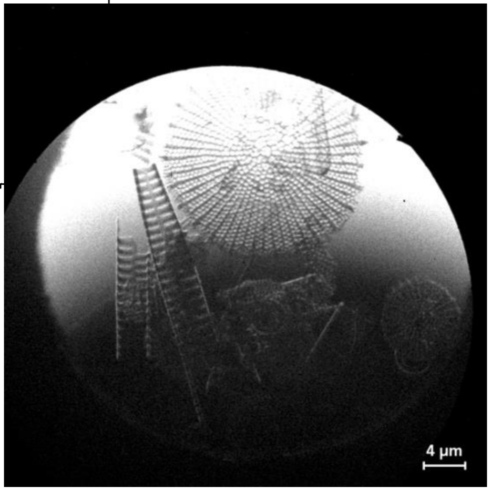
Discharge Source

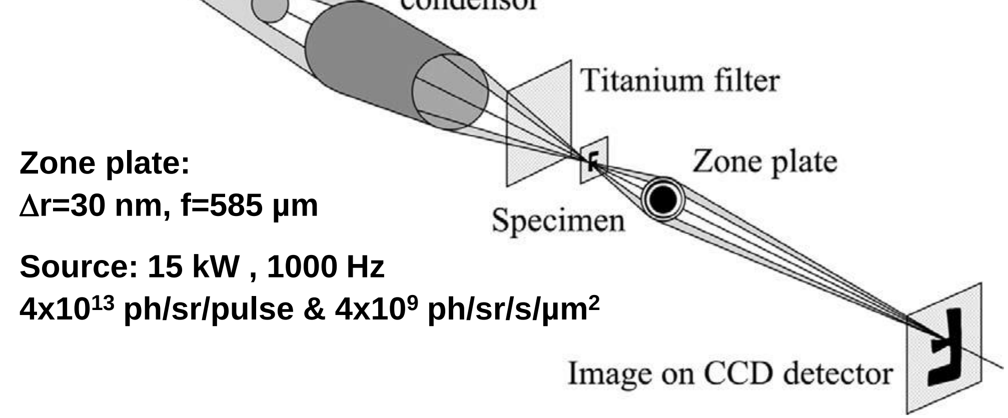
Working gas: Nitrogen

28 W/sr/cm² @ single line at 2.88 nm



Diatom in bright- and dark field illumination mode (due to special illumination of the zone plate)





Zone plate:
Δr=30 nm, f=585 µm

Source: 15 kW , 1000 Hz
4x10^{13} ph/sr/pulse & 4x10^{9} ph/sr/s/µm^{2}

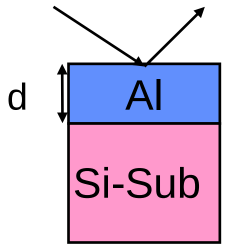
Courtesy of K. Bergmann, M. Benk, FhG ILT, and Th. Wilhein, D. Schäfer, FH Remagen

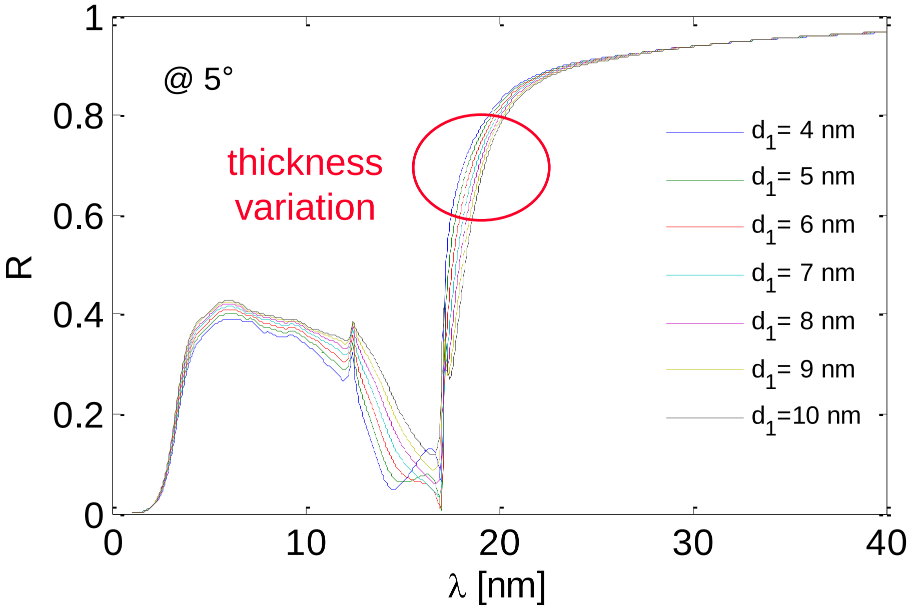
Quick Review: XUV Reflectometry

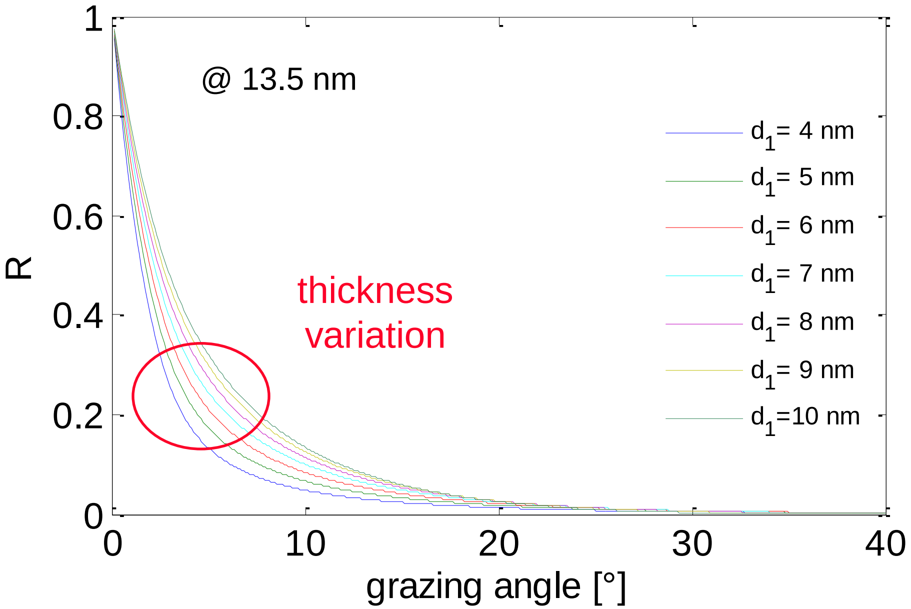
Reflectivity can be measured as:

1.Function of incident angle at fixed wavelength

2.Function of wavelength at fixed angle



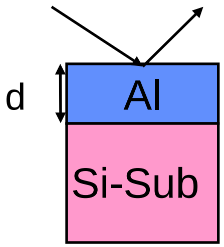


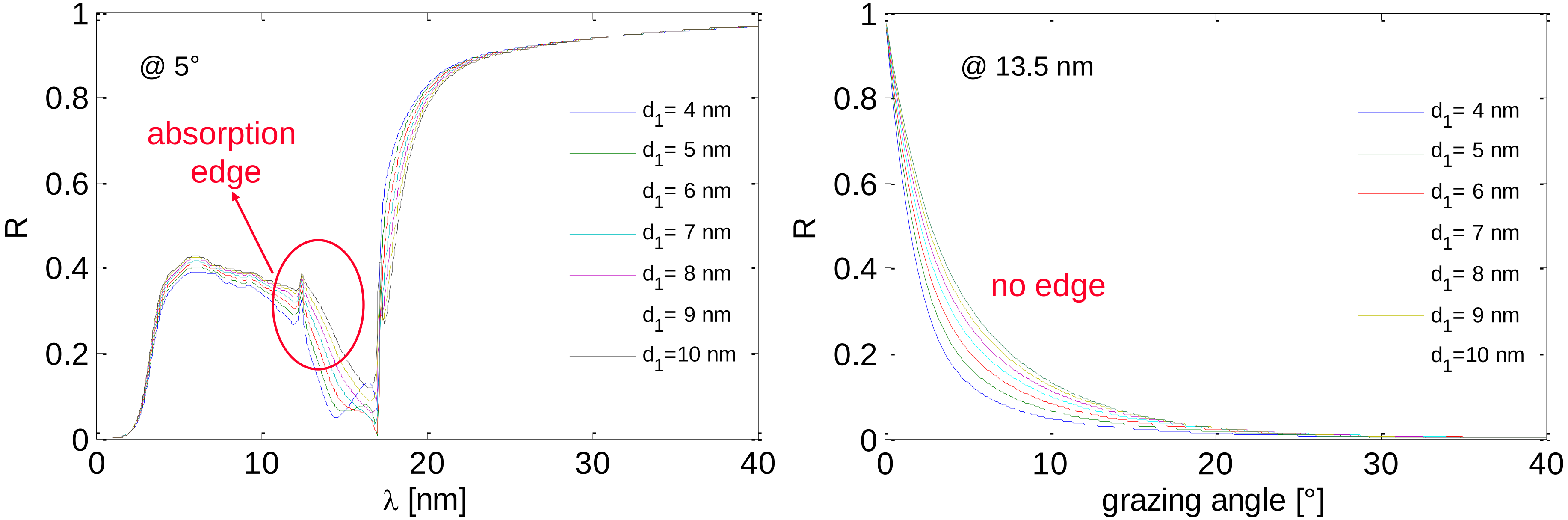


Quick Review: XUV Reflectometry

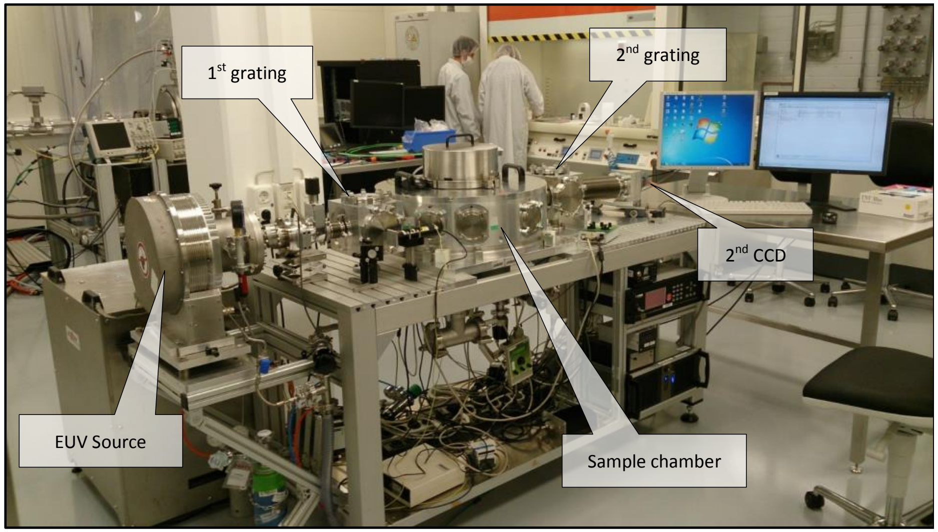
Reflectivity can be measured as:

1. **Function of incident angle at fixed wavelength**
2. **Function of wavelength at fixed angle**

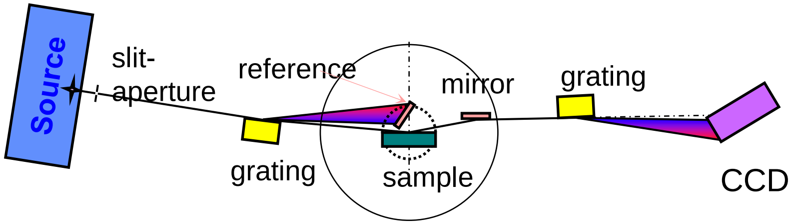




EUV Reflectometer



- Wavelength range: 9 - 17 nm
- Spectral resolution: 5 pm
- Incidence angles: 1 - 15°
- Angular resolution: 0.005°
- Pulse-to-pulse measurements
- Pulse duration: 150 ns
- Thickness sensitivity: ~0.1 nm
- Sample size <100 mm

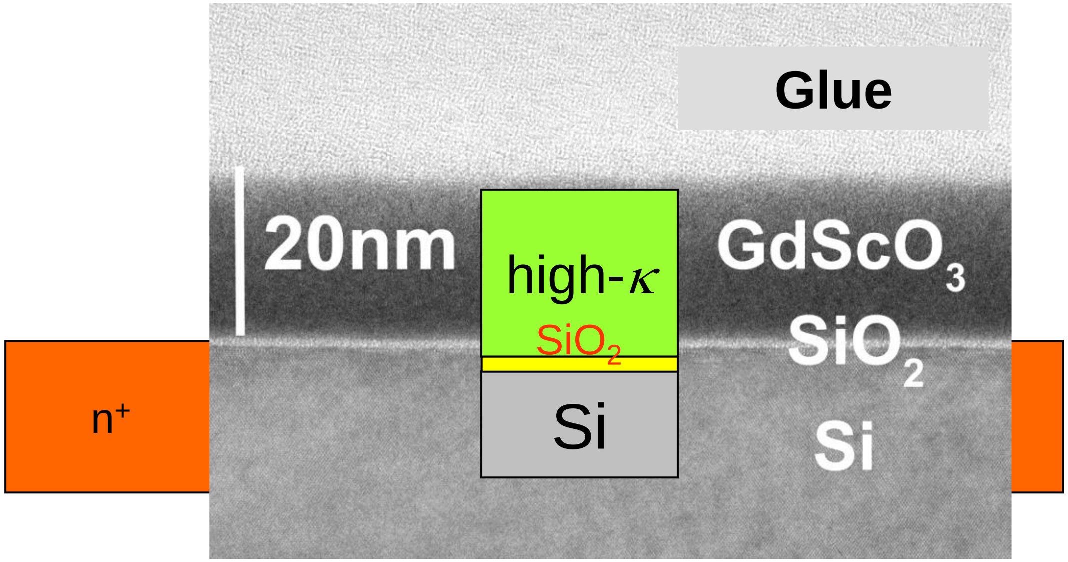


multi angle system (1°-15°)

- non-destructive analysis of ultra-thin films
- determination of chemical bonds (NEXAFS)
- surface sensitive technique (up to ~100 nm)
- surface roughness determination
- high spatial resolution (<< 1 µm)

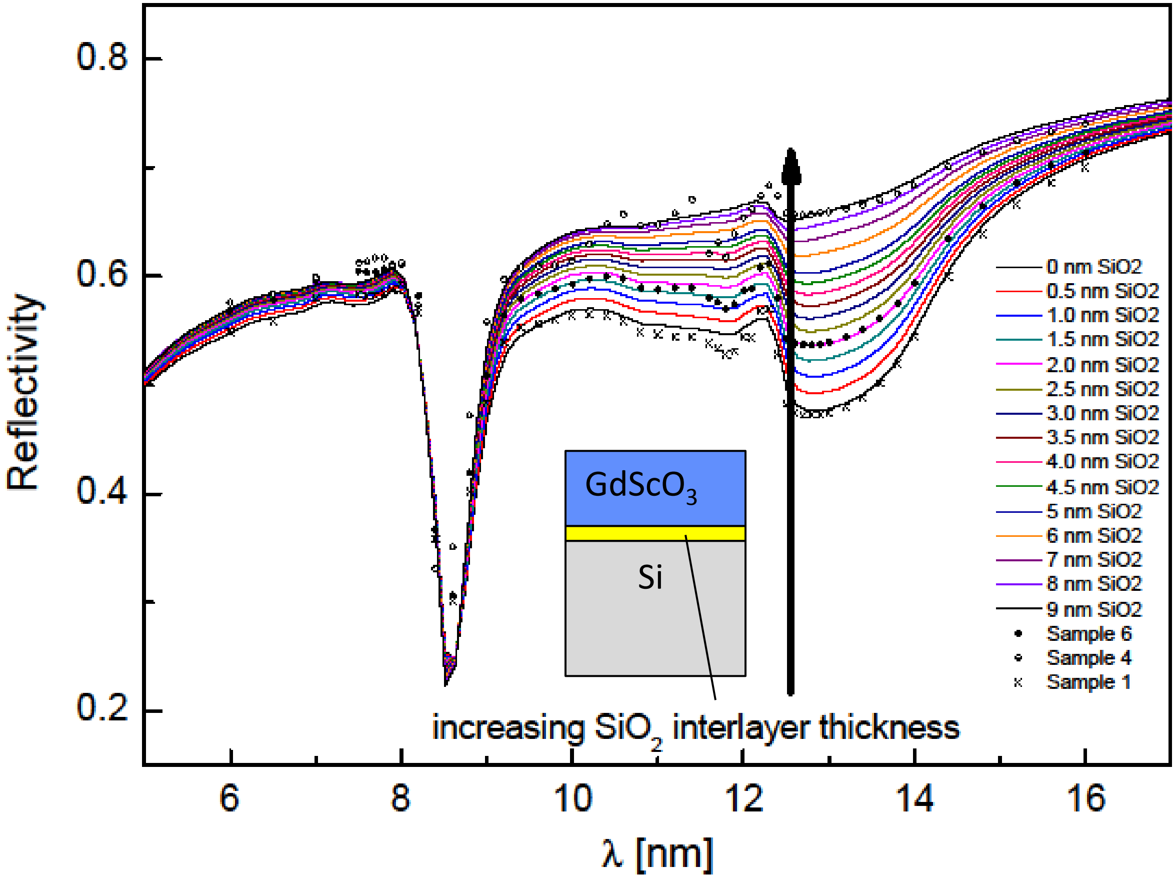
simultaneous acquisition from one measurement

Application example „Parasitic“- Interface



Interfacial layer thickness determination in gate stacks

GdScO$_3$ gate stack with differing „parasitic“ oxide thickness

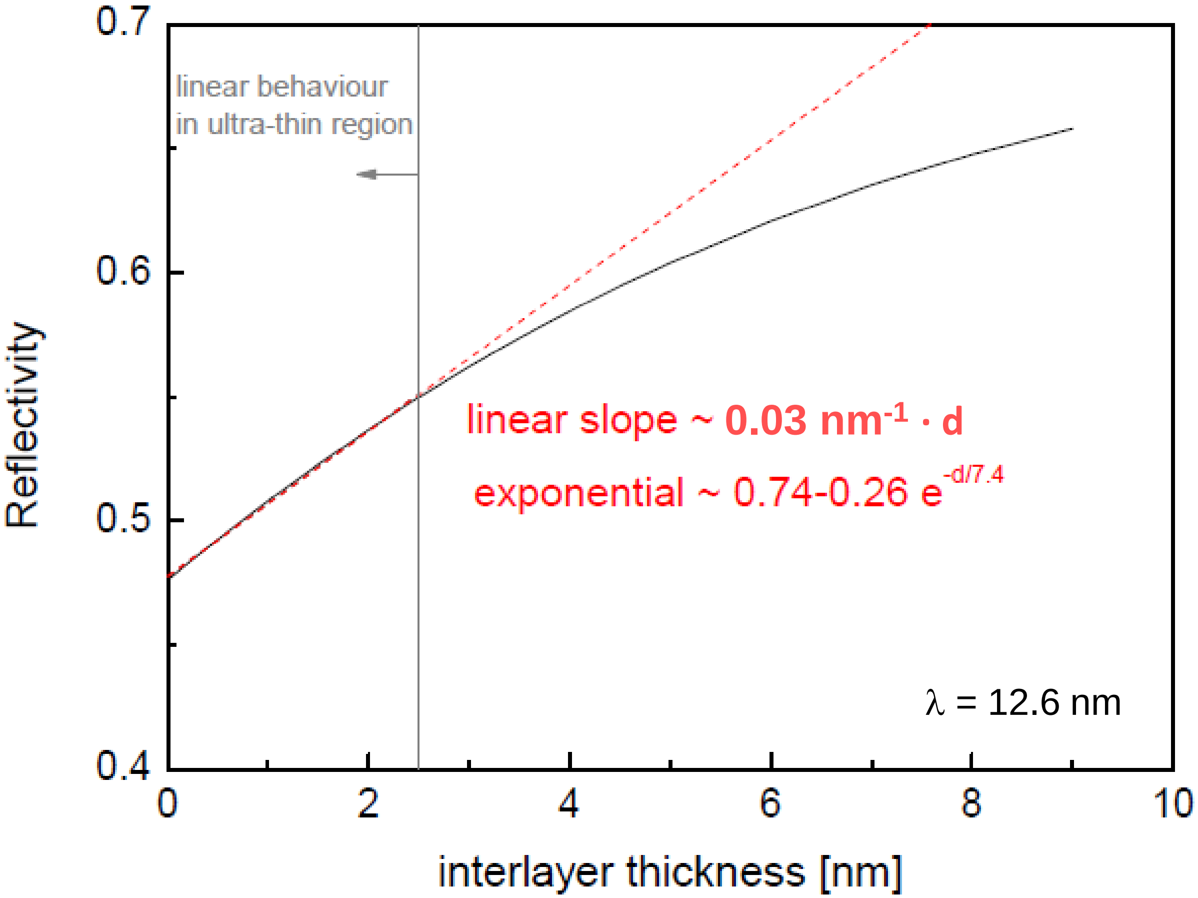


- high contrast for buried ultra-thin interlayer (thickness high-k: 5 nm)
- difficult to access with other all-optical (non-destructive) methods
- characteristic NEXAFS fingerprint at Si L-edge (12.4 nm) visible
- database built-up needed („fingerprint-concept“)

Proof-of-Principle investigations carried out at PTB, BESSY II and in collaboration with J. Schubert (FZJ IBN-1)

Proof-of-Principle Investigations at PTB, BESSY II

GdScO$_3$ gate stack with differing „parasitic“ oxide thickness



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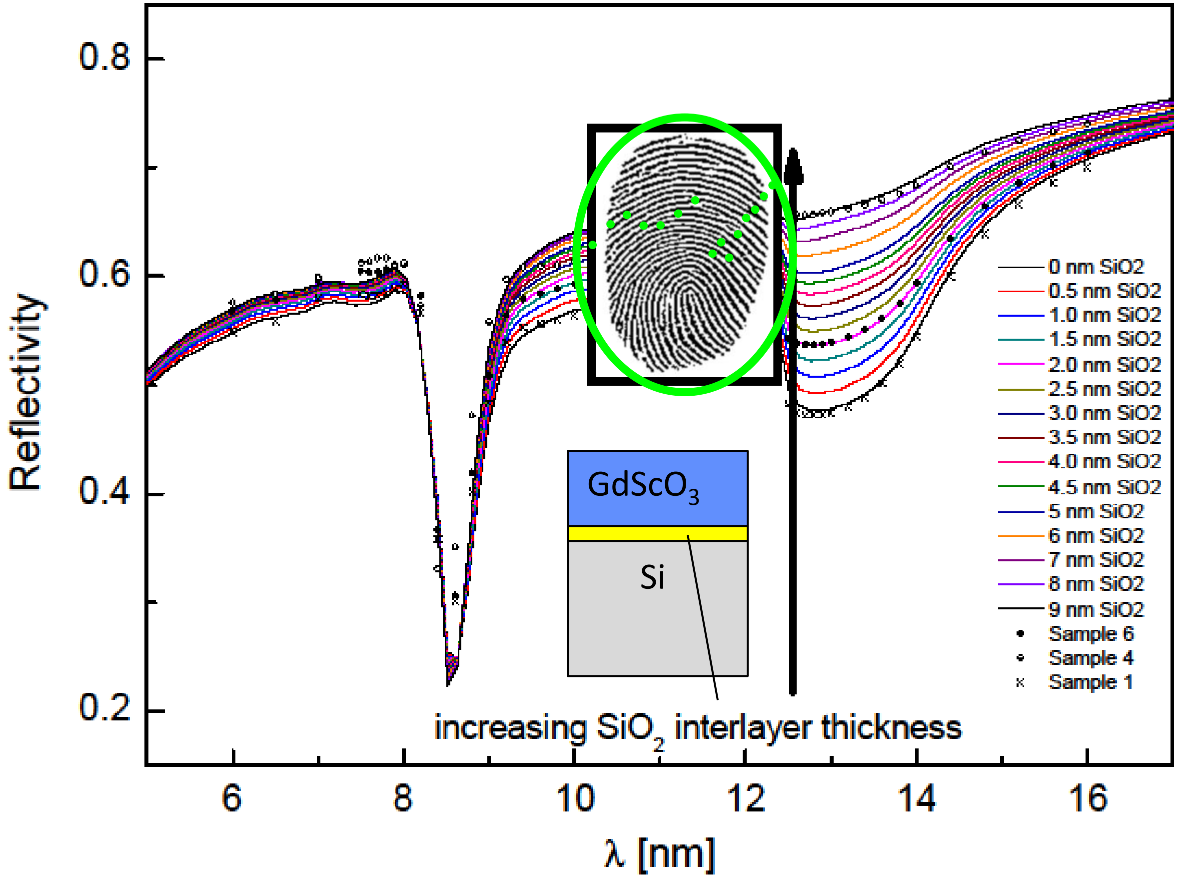

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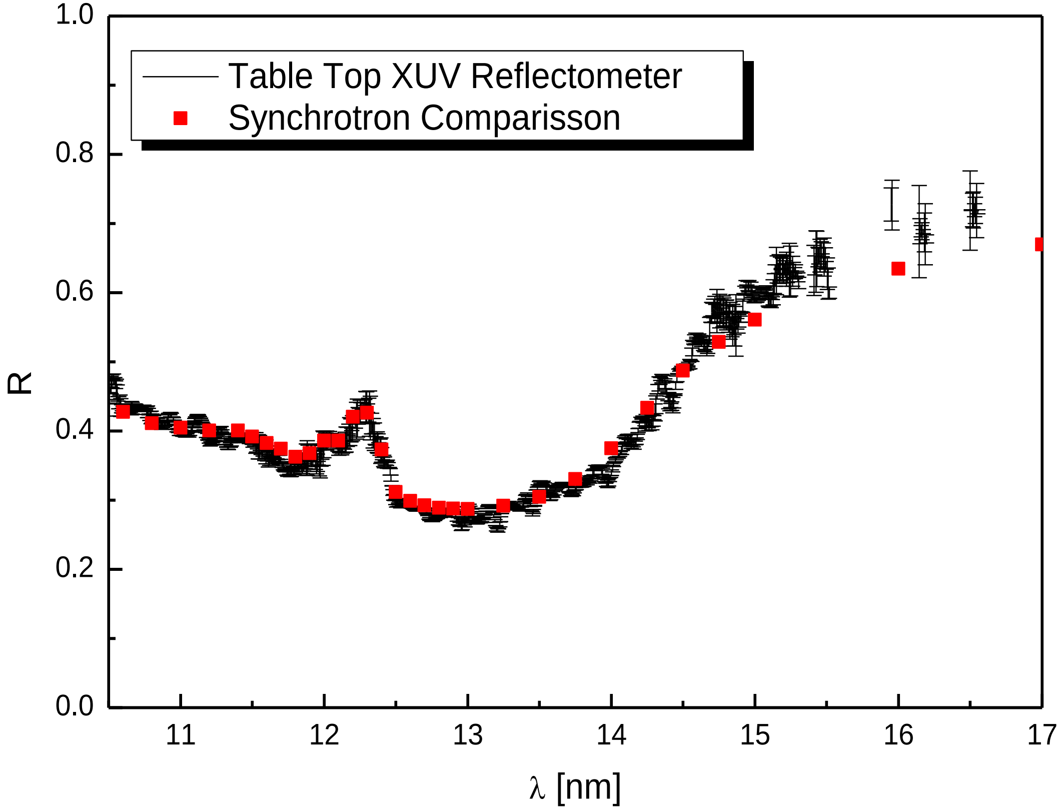
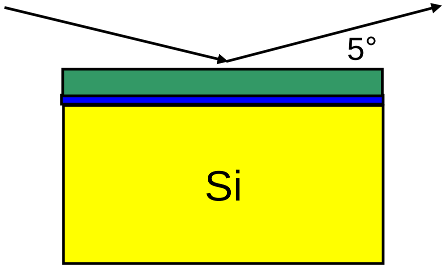
Examples: Burried Ultra-Thin Oxide Layers

Determination of ultra thin HfO_2 layers and burried oxide

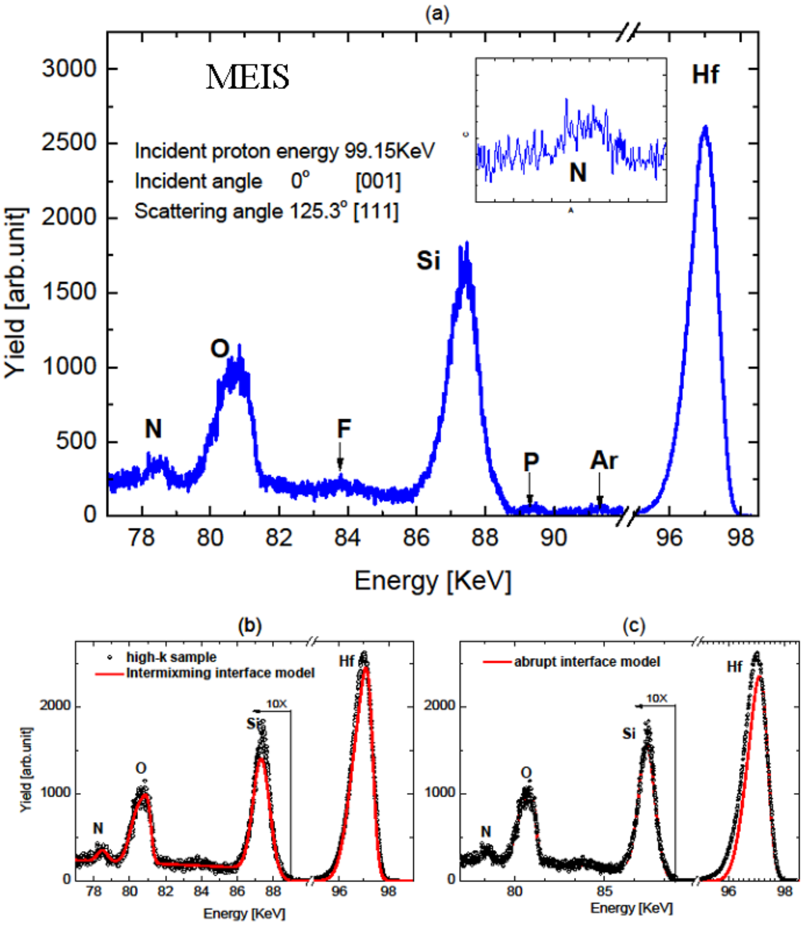


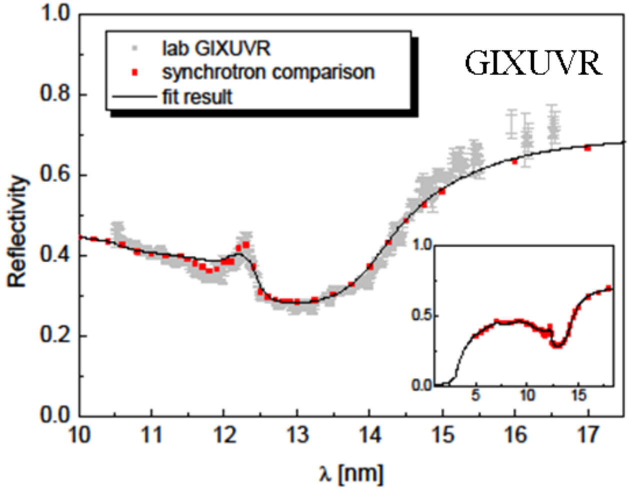


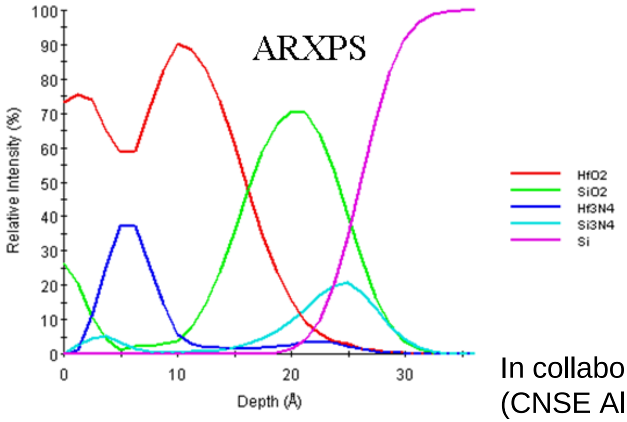
Layer Model:

Hf_3N_4 d: 0.51 nm, density: 12.2 g/cm^3
HfO_2 d: 0.97 nm, density: 9.4 g/cm^3
SiO_2 d: 1.00 nm, density: 2.4 g/cm^3
Si_3N_4 d: 0.83 nm, density: 4.1 g/cm^3
Si substrate
interlayer roughness/diffusion: 0.33 nm

Investigation of a HfO_2 MOS structure by GIXUVR, ARXPS and MEIS







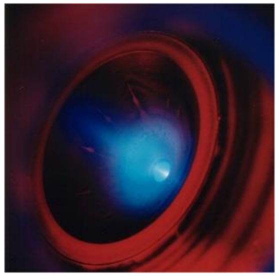
- MEIS: majority of N (~75%) incorporated into HfO_2 layer, likely presence of Hf_3N_4
- ARXPS: nitrogen presence confirmed, diffusion near to the substrate, interdiffuseness ~ 0.5 nm
- GIXUVR: agreement with ARXPS results, deviations from bulk densities required to generate best fit

In collaboration with M. Liehr et. al. (CNSE Albany, USA)

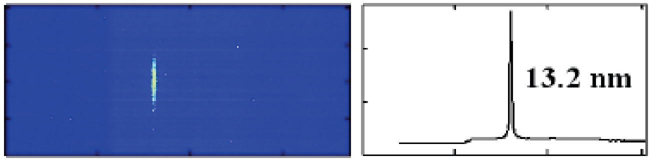
Benchmarking: XUV als Metrology Tool

Technique	In	Out	Property monitored	destructive	Non-destructive	Vacuum [mbar]	Typ. Depth of Analysis Typ. Spatial Resolution	Typ. Measuring time
Ellipsometry	Photon	Photon	polarization		•	-	> 5nm (not all mat.) 1-100 µm	ms – s
XRR	Photon	Photon	Intensity		•	-	>>100 nm > 50 µm	minutes – hrs
AFM	-	-	Deflection	•	•	-	Surface only 0.1 – 10 nm	Hours
TEM	Electron	Electron	Intensity	•		<1E-8	~ 100 nm thin films << 1 nm	Sec-min
SEM	Electron	Electron	Intensity		•	<1E-8	Surface only ~ 1 - 5 nm	Sec-min
XPS	Photon	Electron	Energy		•	<1E-8	10 nm > 50 µm	>hour
AES	Photon	Electron	Energy		•	<1E-9	1- 3 nm 50 nm	>hour
RBS	Ion	Ion	Energy	•		1E-6 - 1E-9	1 µm 1 mm	minutes – hrs
SIMS	Ion	Ion	Mass	•		1E-6 - 1E-9	1 – 10 nm 1 mm – 0.5 µm	minutes – hrs
GIXUVR	Photon	Photon	Intensity		•	1E-2 - 1E-6	< 100 nm ~ µm – nm	ms – s

Outlook



XUV plasma based sources
- new very efficient technology
- “Aachener Lampe” successfully used in EUVL & metrology



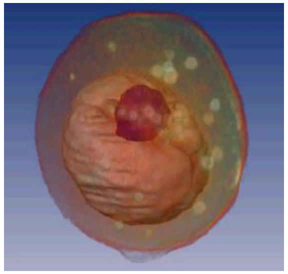
High brilliance metrology sources
- small emitting volume
- XUV lasers

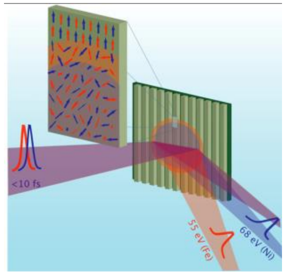
future research challenges

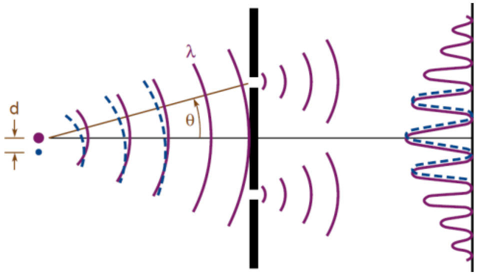
3d imaging
- combining of lateral and in-depth resolution
- cell nanotomography

Spectro-microscopy
- combining of spectral and lateral resolution
- magnetic domains

Coherence
- holography
- lens less imaging
- interference litho







Thank you very much for your attention!