Source radiance requirements for EUV microscopes

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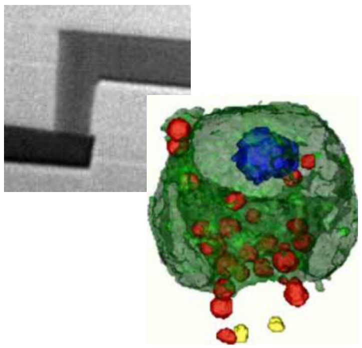
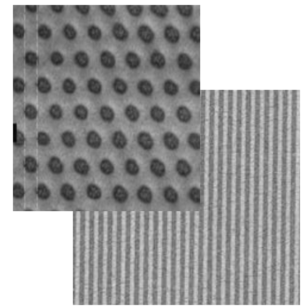
Applications

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



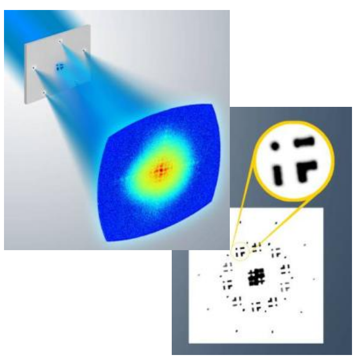
Microscopy

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



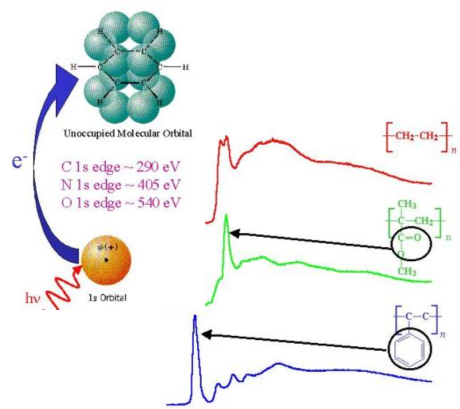
Patterning

- 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

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Compromise between source characteristics and application needs

Given source characteristics

Spectral radiance:

radiation energy (photons) per time interval, wavelength, solid angle and area

polarization

emitting volume

coherence properties

Variety of application needs

spectral characteristics

spatial resolution

time resolution

irradiance

sensitivity

dose

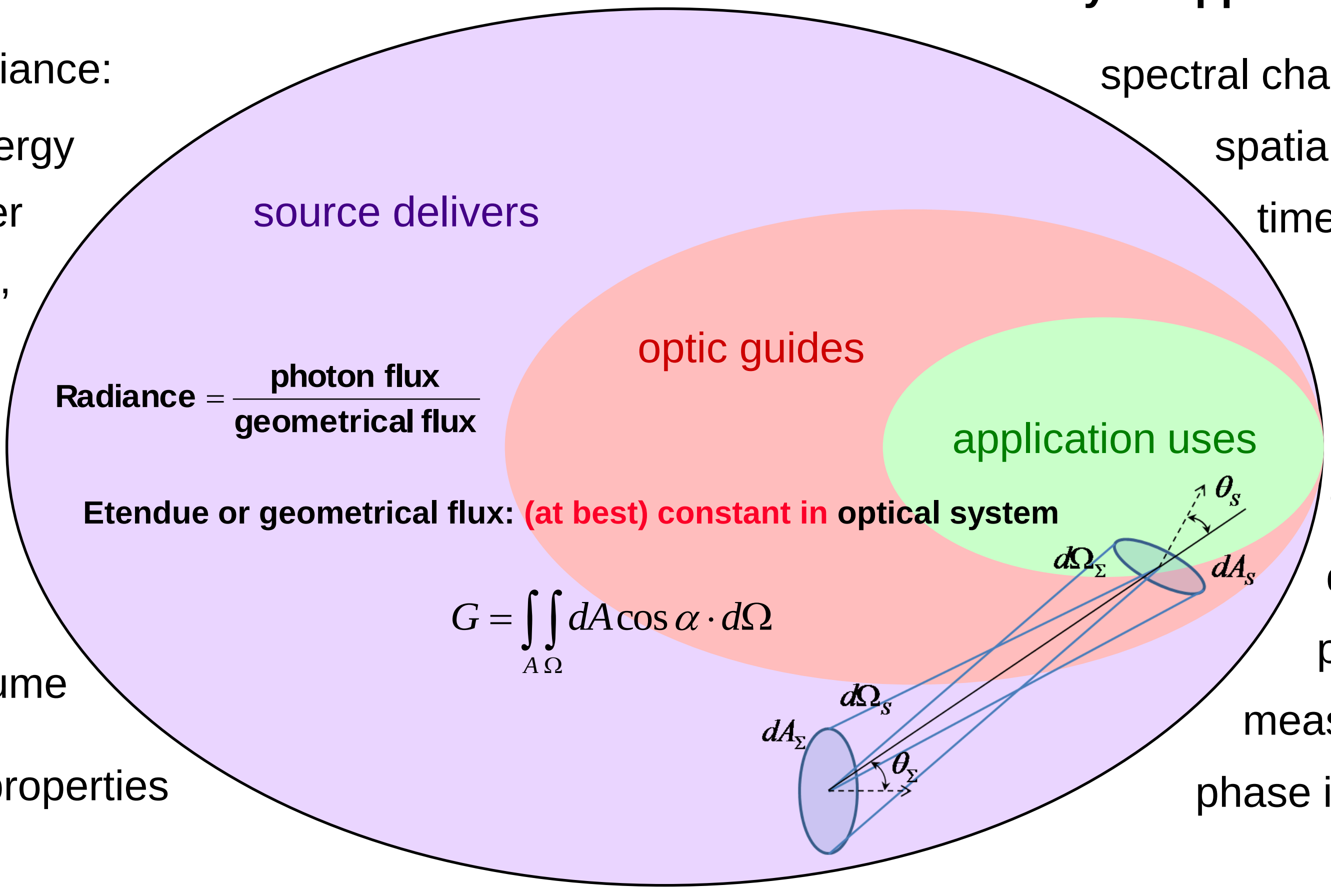
throughput

divergence

polarization

measuring spot

phase information



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Etendue or geometrical flux

$$G = \int_A \int_\Omega dA \cos\theta \cdot d\Omega = \pi \cdot NA^2 \cdot A$$ → **constant in optical system (at best)**

***NA* – numerical aperture**
***A* – field of view area**

$$\text{Radiance} = \frac{\text{photon flux}}{\text{geometrical flux}}$$

not increasing (Radiance), *not increasing* (photon flux), *not decreasing* (geometrical flux)

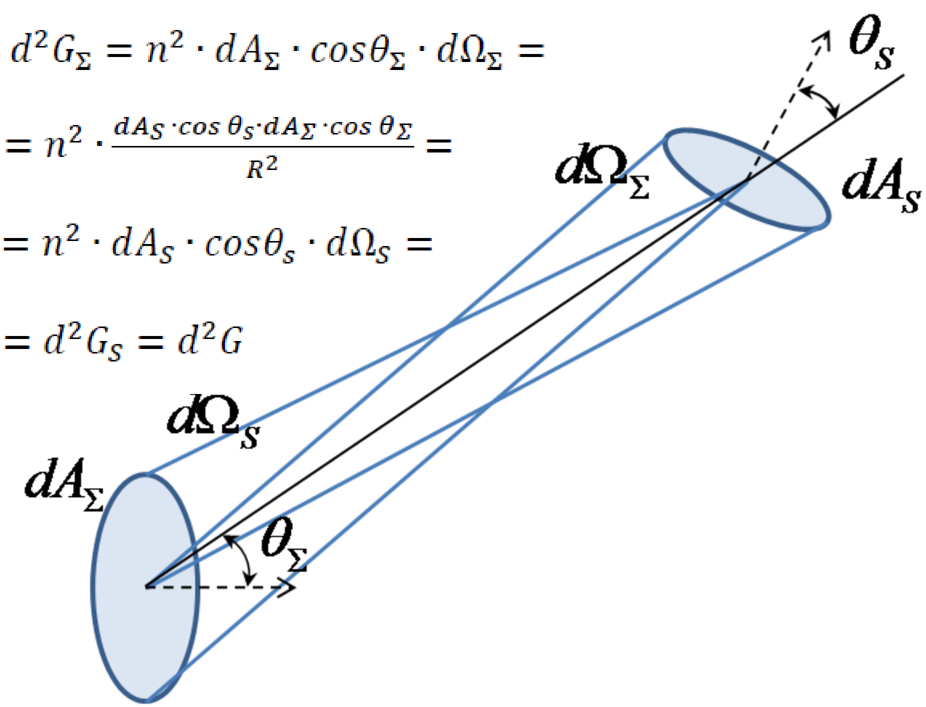
$$L = \frac{d^2\Phi}{dA \cdot \cos\theta \cdot d\Omega} = n^2 \cdot \frac{d^2\Phi}{d^2G}$$

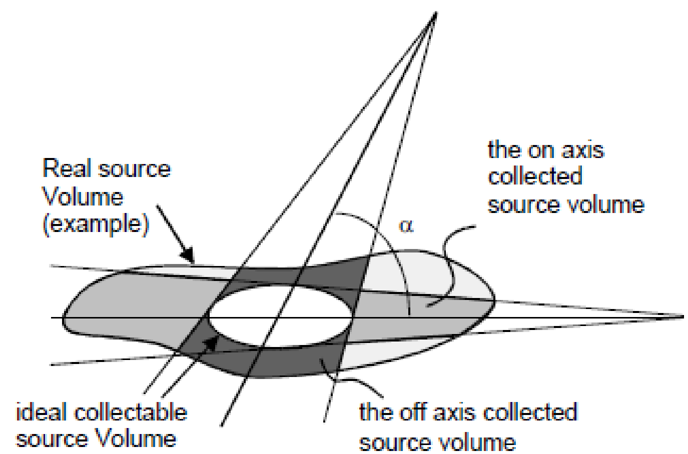
$$d^2G_\Sigma = n^2 \cdot dA_\Sigma \cdot \cos\theta_\Sigma \cdot d\Omega_\Sigma =$$

$$= n^2 \cdot \frac{dA_S \cdot \cos\theta_S \cdot dA_\Sigma \cdot \cos\theta_\Sigma}{R^2} =$$

$$= n^2 \cdot dA_S \cdot \cos\theta_s \cdot d\Omega_S =$$

$$= d^2G_S = d^2G$$





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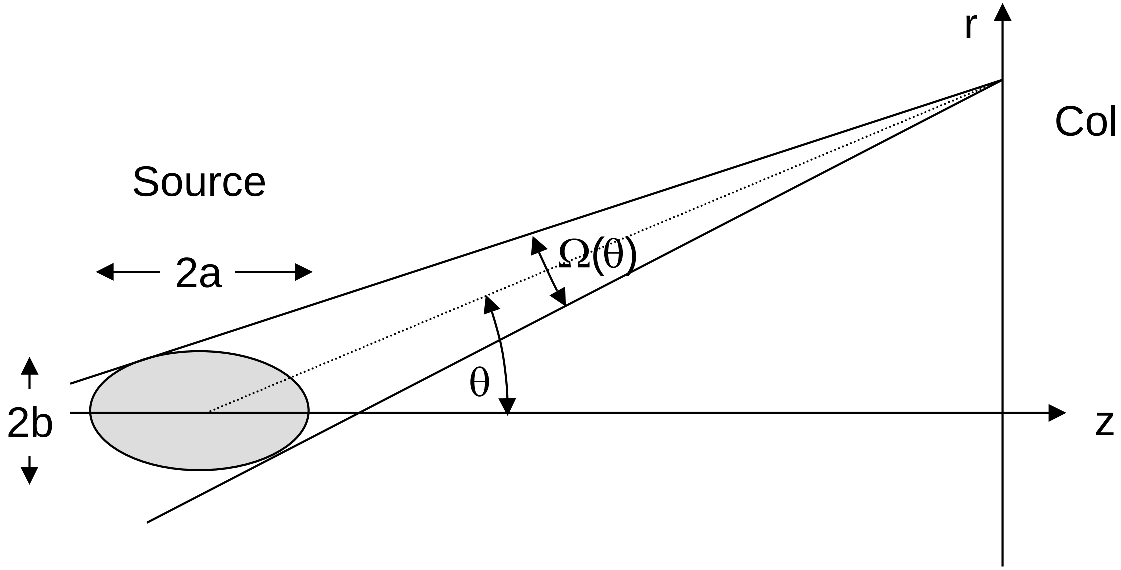
Etendue of an elliptical source



Usable etendue of a volume elliptical source as a function of collector half-opening angle *θ* and ellipsoid semi-axes *a* and *b*

$$G_{Quelle} = 2\pi^2 b^2 \int_{\theta} \sin\theta \cdot \sqrt{1 + \frac{a^2}{b^2}\tan^2\theta} \cdot d\sin\theta$$

G. Derra and W. Singer, "Collection efficiency of EUV sources", Emerging Lithographic Technologies VII, Proc. Of SPIE, Vol. 5037, p.728-741, 2003

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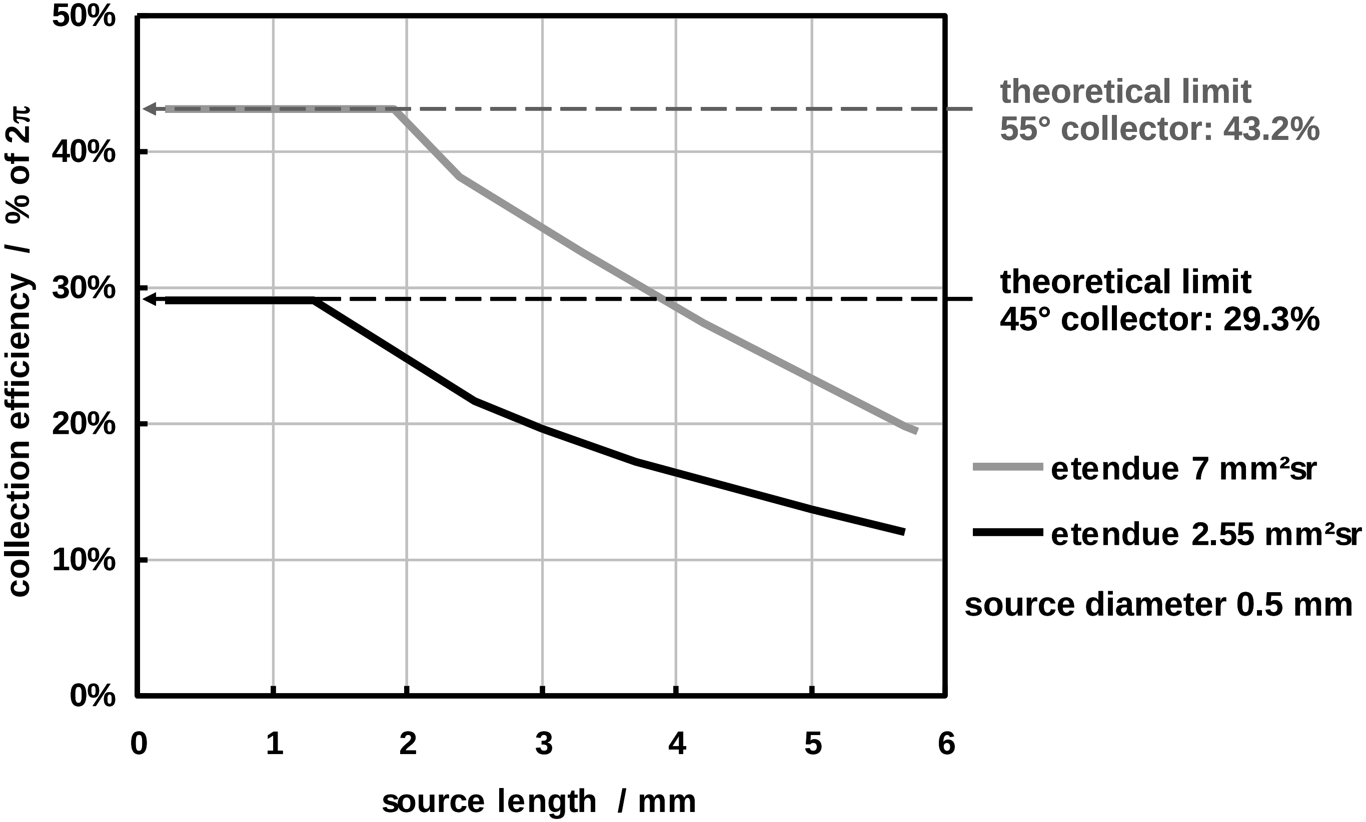
Collection efficiency of a volume source



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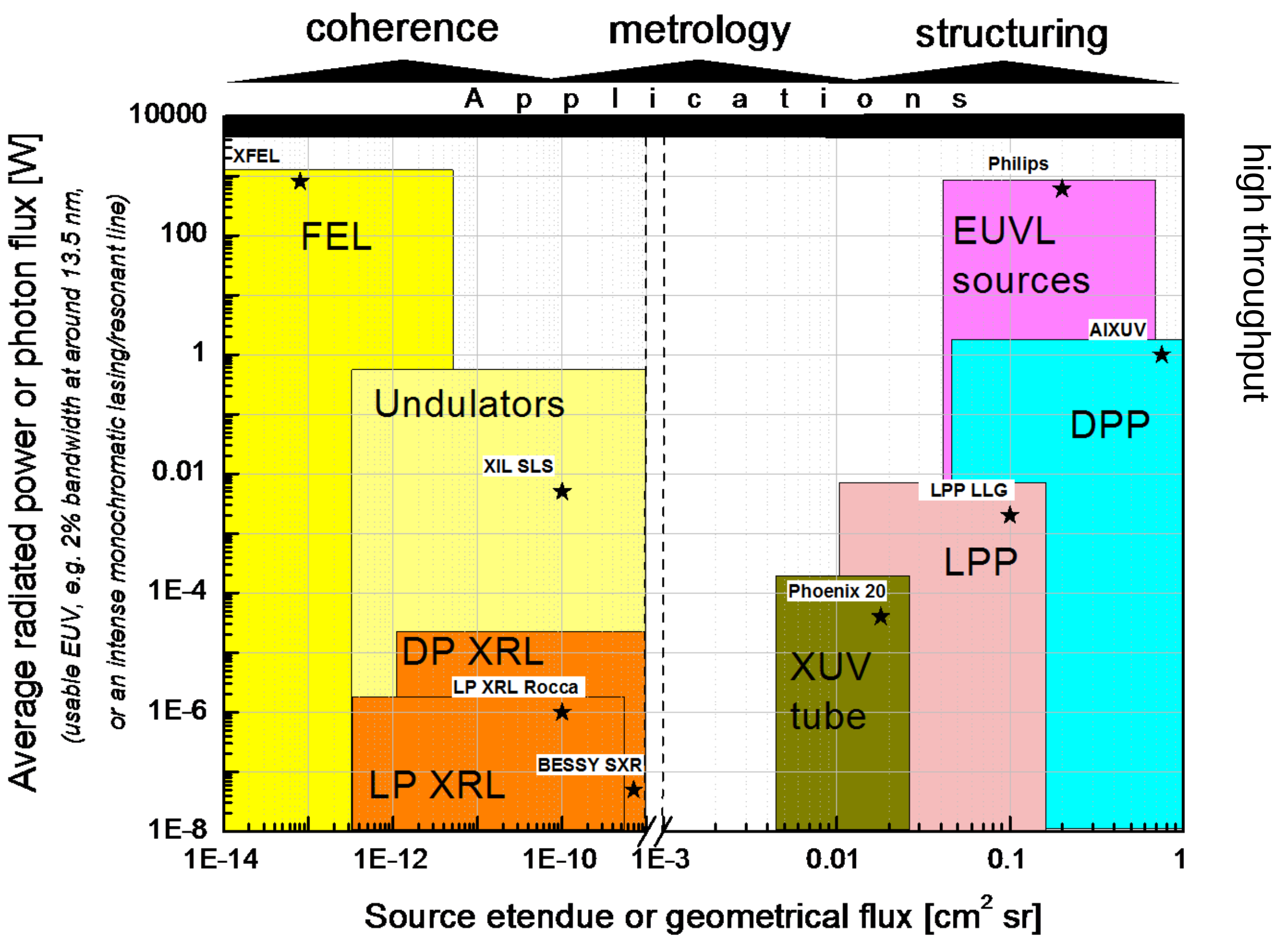
Average power (of usable bandwidth) and etendue of different source concepts and existing sources



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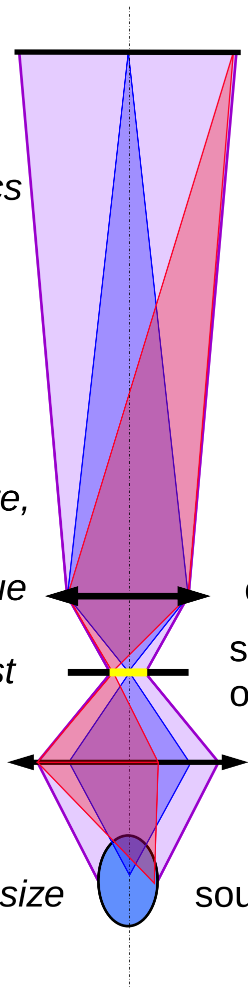
Source requirements for resolution matched microscopy



NA = 0.61 x *λ/RES* ~ 0.2 – 0.3 needed for resolution
=> *Ω* = 0.1 – 0.5 sr radiation solid angle at sample

Magnification determined by resolution and detector pixel size
=> object field limitation through detector size and magnification

Etendue used by microscopy application ~ 10^{-8} – 10^{-6} cm^2sr

Available incoherent sources: 10^{-2} – 10^{-1} cm^2sr

Synchrotron based sources and XRLs: < 10^{-9} cm^2sr

Necessary irradiation dose at sample is determined by contrast, photon energy, pixel size, magnification, detector quantum efficiency, and transmission of imaging optics and sample: 1 – 1000 mJ/cm^2.

Minimal exposure time determined by CCD read-out speed

=> required average source radiance ~ 10^{-2} – 10 W/(cm^2sr) within usable radiation bandwidth (one monochromatic line for zone plate or ~ 3 – 4 % for multilayer based optics)

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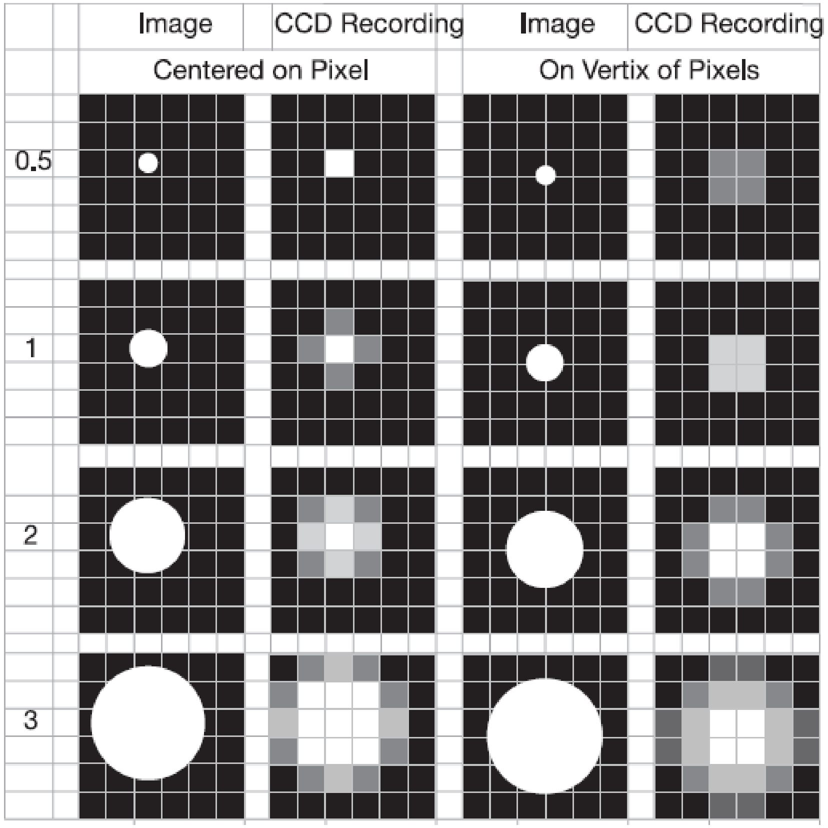
Resolution matched imaging



It is only when the object image covers three pixels do we start to obtain an image that is more faithfully reproduced, and clearly represents a circular object.

$$M = 3 \cdot pix/RES$$

ANDOR TECHNOLOGY

Digital Camera Fundamentals

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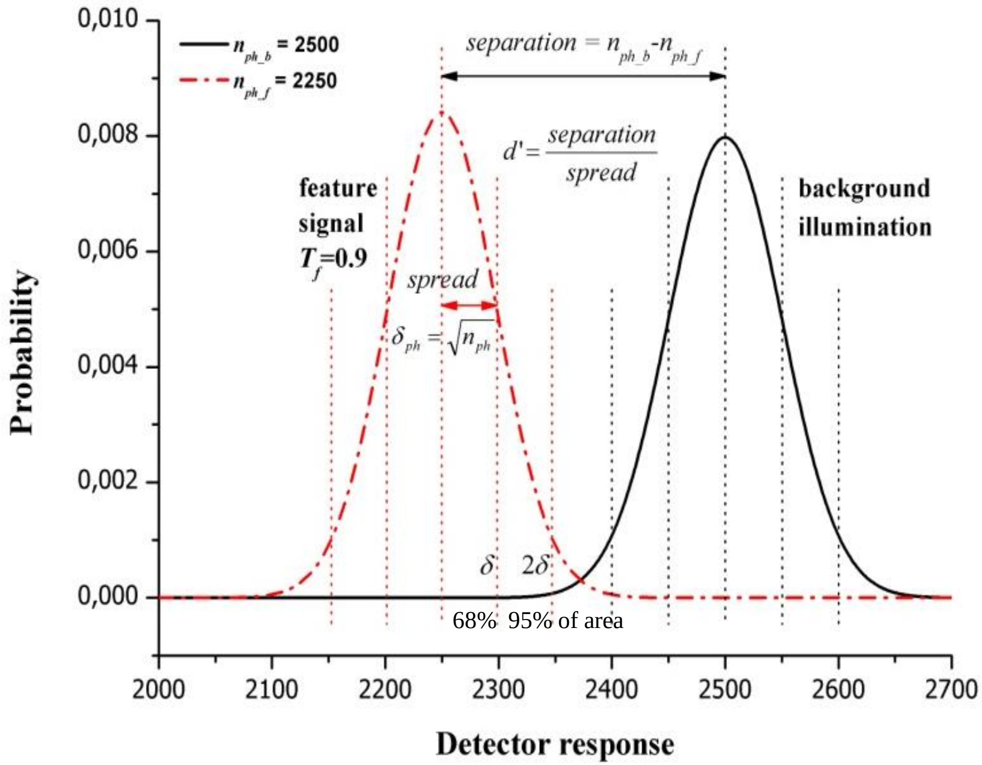
Sensitivity index

photon detections → Poisson statistics

Photon noise: $\delta_{ph} = \sqrt{n_{ph}}$



Sensitivity index:

$$d' = separation\ /\ spread \cong$$
$$\cong (n_{ph\_f} - n_{ph\_b})/\sqrt{n_{ph\_b}}$$

d' of at least 5 is needed for 100% certainty in distinguishing image features

For further information see "Signal Detection Theory" or A. Rose, "Television pickup tubes and the problem of vision", in "Advances in Electronics" ***1****, 131-166 (1948)*

Quasi-ideal detector (signal noise dominating):

$$d'_{det} \simeq \frac{(n_{e^-max} \cdot QE \cdot n_{ph\_f}) - (n_{e^-max} \cdot QE \cdot n_{ph\_b})}{\sqrt{n^2_{e^-max} \cdot QE \cdot n_{ph\_b}}} =$$

$$= \sqrt{QE} \cdot \frac{n_{ph\_f} - n_{ph\_b}}{\sqrt{n_{ph\_b}}} = \sqrt{QE} \cdot d'$$

Required number of photons:

$$n_{ph\_b} \geq \frac{25}{QE \cdot C^2}$$ with contrast $C = \frac{n_{ph\_f} - n_{ph\_b}}{n_{ph\_b}}$

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Detector influence

Noise:

$$Noise = \delta_{total} = \sqrt{\delta^2_{readout} + F^2 \cdot M^2 \cdot (\delta^2_{dark} + \delta^2_{CIC} + \delta^2_{signal})}$$

- sensor readout noise (crucial if fast readout needed)
- amplification: gain M; noise factor F (additional noise)
- dark (thermal) noise (temperature and time dependent)
- spurious noise (clock induced charge, small)
- the noise from the signal itself (photon noise)

Signal:

$$Signal = M \cdot n_{\max} \cdot QE \cdot P, \quad \delta_{signal} = n_{\max} \cdot \sqrt{QE \cdot P}$$

$$\frac{Signal}{Noise} = \frac{n_{\max} \cdot QE \cdot P}{\sqrt{\cancel{F}^2 \cdot (n^2_{\max} \cdot QE \cdot P + \cancel{N}_{dark} + \cancel{\delta}^2_{CIC}) + \delta^2_{readout} / \cancel{M}^2}}$$

A reasonably high level of confidence of signal detection requires signal noise be greater than others:

$$P \geq \frac{\delta^2_{readout}}{n^2_{\max} \cdot QE} \sim 1$$

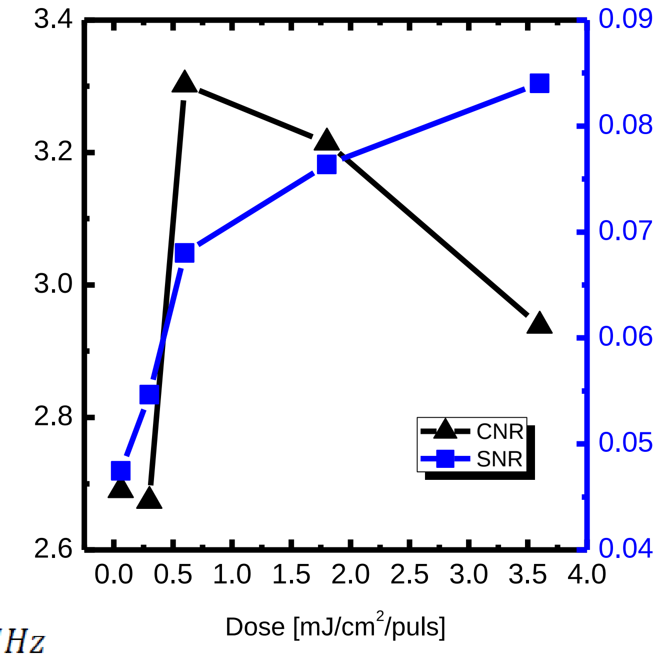
$\delta_{readout} \approx 3\ e^- \ @\ 30\ kHz$ (35 s readout of 1024x1024)

$\approx 10\ e^- \ @\ 1\ MHz$ (1 s readout)

$n_{ph} \gtrsim 1\ @\ 30\ kHz$ and $\gtrsim 15\ @\ 1\ MHz$

Image contrast

$\frac{(I_{\max} - I_{\min})}{\sigma_{BKG}}$ ↓ $\frac{(I_{\max} - I_{\min})}{I_{BKG}}$ ↓



The Rose criterion: Signal/Noise ≥ 5 needed for 100% certainty in distinguishing image features: $P > \frac{25}{QE \cdot C^2} > 60$

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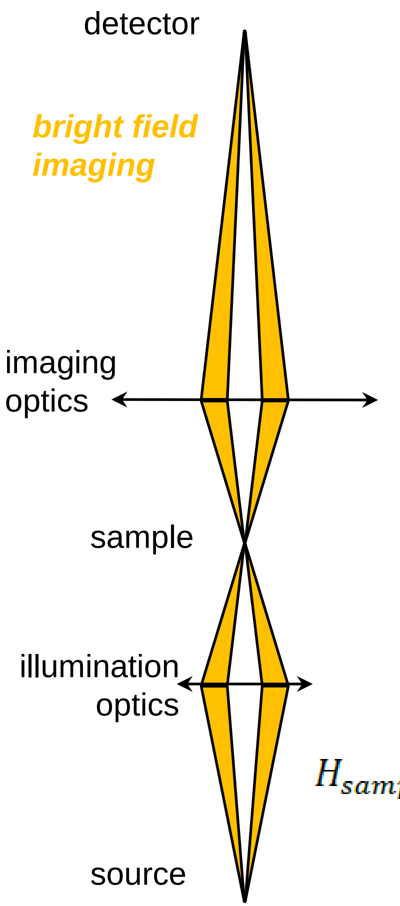
Requirements on source radiance – bright field microscopy



Bright field amplitude contrast microscopy

$$C_{bf} = \frac{n_{ph\_feature} - n_{ph\_bg}}{n_{ph\_bg}} = T_{feature} - 1$$

$$L_{source} = \frac{25 \cdot fps \cdot h \cdot c / \lambda}{QE \cdot C_{bf}^2 \cdot T_{illumination} \cdot T_{s\_bg} \cdot T_{imaging} \cdot \pi \cdot NA_{imaging}^2 \cdot A_{field} / N_{pixel}^2}$$

Resolution matched imaging

$$M = 3 \cdot pix/RES$$

$$A_{field} = (N_{pixel} \cdot pix/M)^2 = (N_{pixel} \cdot RES/3)^2$$

$$L_{source} \cong \frac{4}{(T_{feature}-1)^2 \cdot T_{system}} \cdot \frac{fps_{[s^{-1}]}}{\lambda_{[nm]}^3} \quad \frac{W}{cm^2 sr}$$

wavelength	2.88	13.5	nm
T feature	0.7	0.5	
T System	0.01	0.02	
fps	0.1	1	s^{-1}
radiance	27.0	0.30	$W/cm^2/sr$

Minimum radiant exposure per image

$$H_{sample} = \frac{\Phi_{sample}}{A \cdot fps} = \frac{L_{source} \cdot T_{illumination} \cdot G}{A \cdot fps} = L_{source} \cdot \pi \cdot NA^2 \cdot T_{illumination} / fps =$$

$$= \frac{25 \cdot hc/\lambda}{QE \cdot C^2 \cdot T_{sample\_b} \cdot T_{imaging} \cdot (RES/3)^2} \cong 13.5 \frac{mJ}{cm^2} \ @\ C = -0.5 \ and \ \cong 340 \frac{mJ}{cm^2} \ @\ C = -0.1$$

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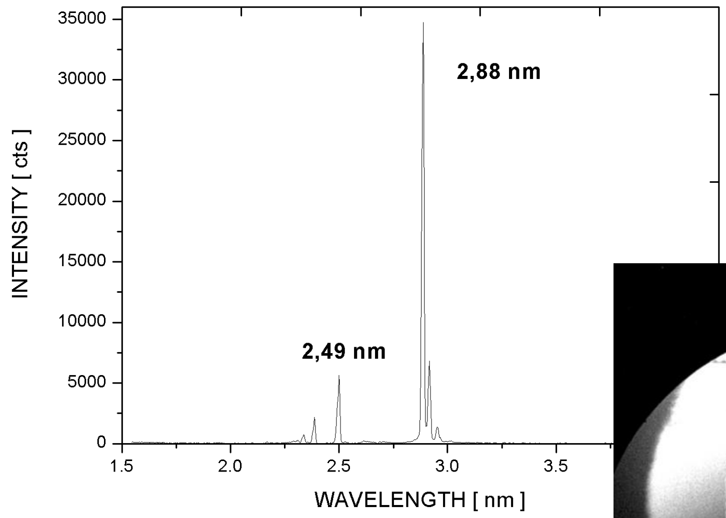
XUV microscopy: Soft x-ray microscopy (Water Window)

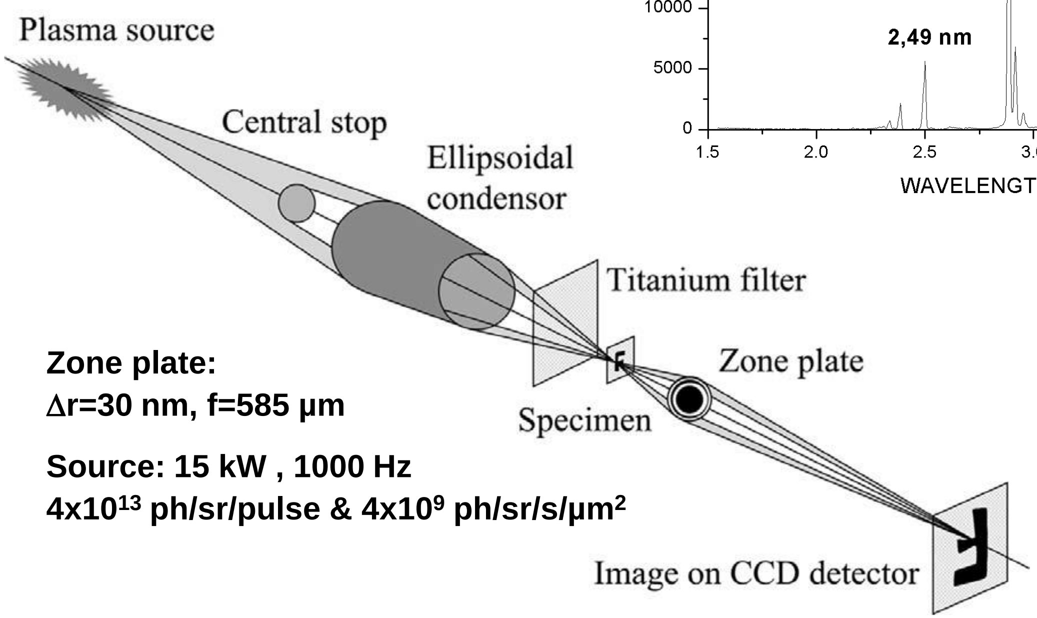
Discharge Source

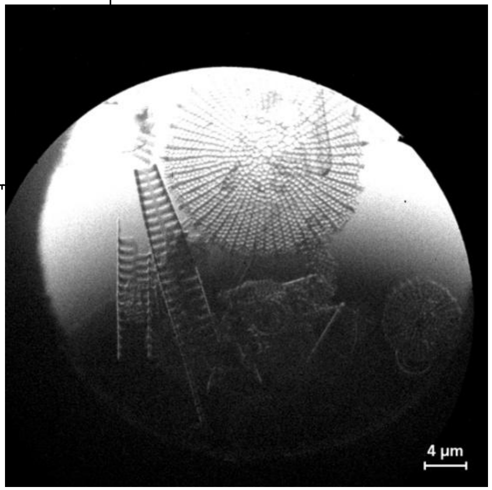
Working gas: Nitrogen

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/µm²

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

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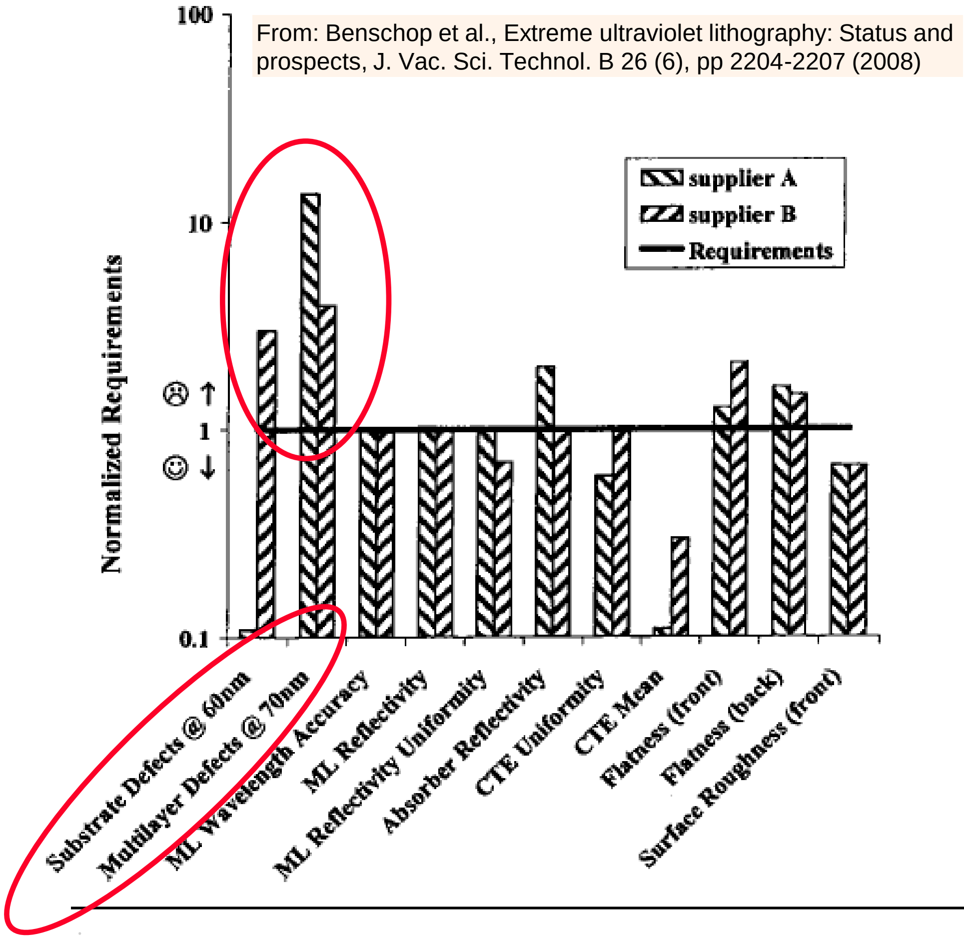
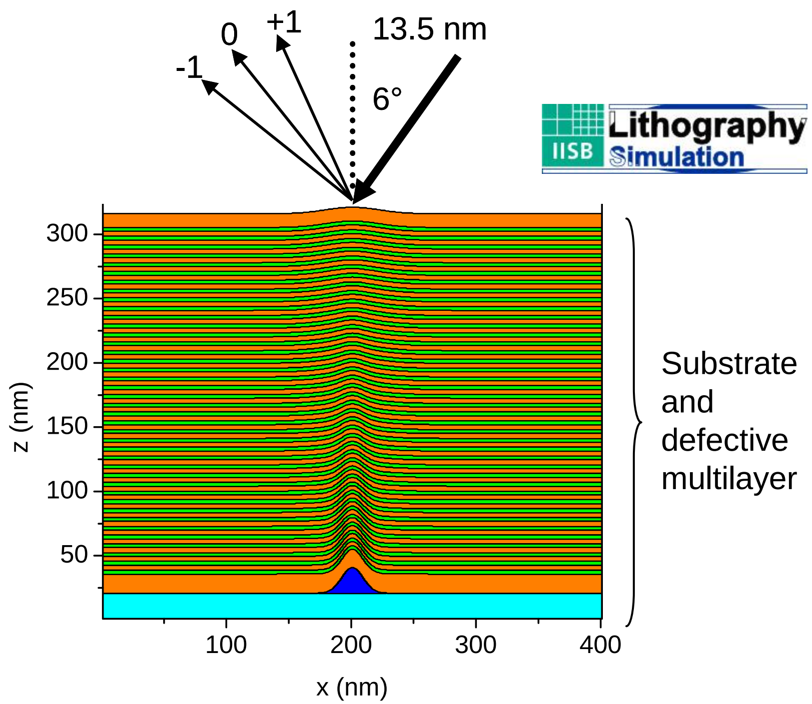
Application: at-wavelength mask blank inspection for EUVL

Best data observed to date relative to specification of EUV mask blank requirements for two suppliers



- mask defects - the leading challenge
- requirements for mask substrates: zero defects at >50 nm defect size
- for mask blanks zero defects >30 nm



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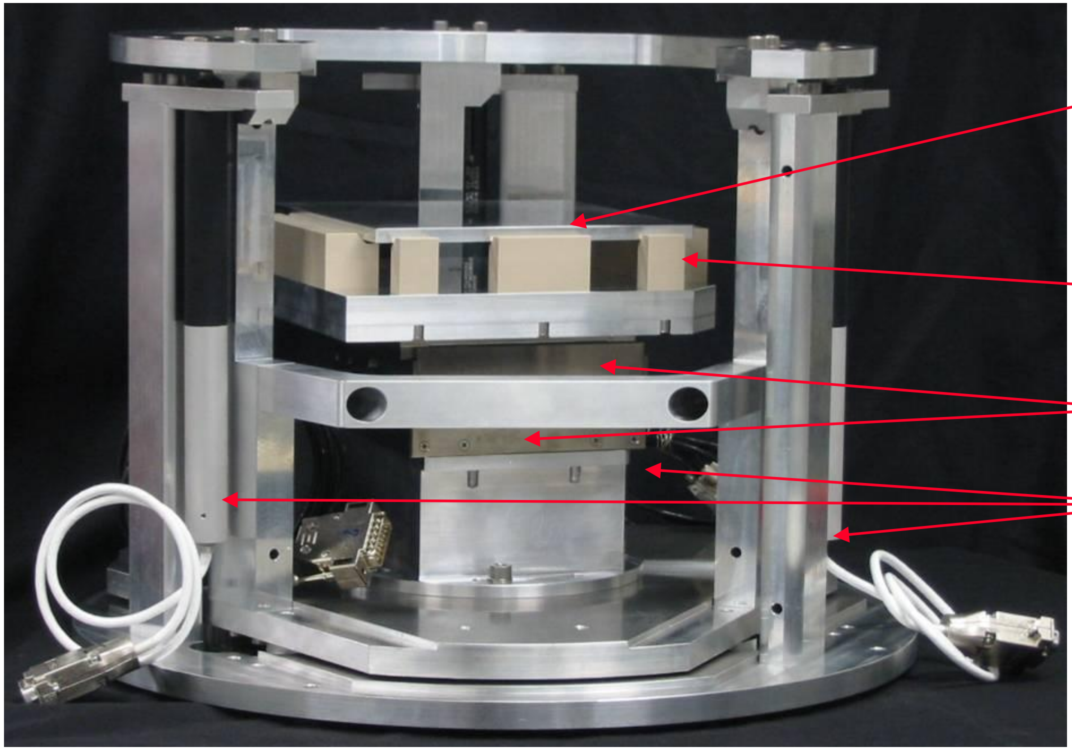
Mask blank holder and positioning system



Mask

Mask holder

x,y-movement

z-movement

15 cm

15 nm

7 orders of magnitude

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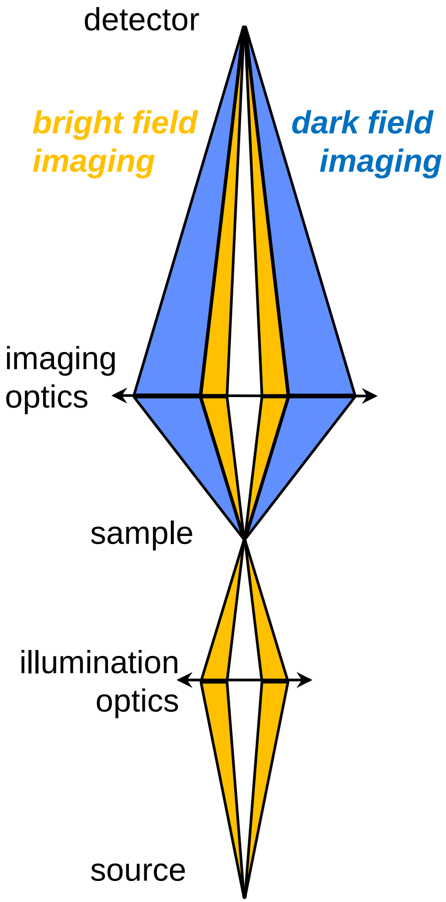
Requirements on source radiance – dark field microscopy



With a 2048 x 2048 detector's pixel array the object field in our example of resolution matched microscopy is about: $A = (N \cdot RES/3)^2 = 3.4 \cdot 10^{-6}\ cm^2$

This will result in about 2 years of exposure for a complete inspection of a 15 x 15 cm^2 mask for EUV lithography with a high resolving microscope and reasonable detector readout rates and source radiances .

=> concept change is needed

Sensitivity matched dark field microscopy (scatterometry)

$$C_{df} = \frac{n_{ph\_d} - n_{ph\_s}}{n_{ph\_d}} = 1 - \frac{n_{ph\_s}}{n_{ph\_d}}$$

probability of finding a scattered particle within a given solid angle

with $\sigma_{imaging} = \int_{\Omega_{imaging}} \frac{d\sigma}{d\Omega} \cdot d\Omega$

surface roughness scatter

and contrast $C_{df} = 1 - \frac{\sigma_{im\_s}}{\sigma_{im\_d}}$

defect scatter

$$L_{source} = \frac{25 \cdot fps \cdot h \cdot c/\lambda}{QE \cdot C_{df}^2 \cdot T_{illumination} \cdot T_{imaging} \cdot \pi \cdot NA_{illumination}^2 \cdot \sigma_{imaging}}$$

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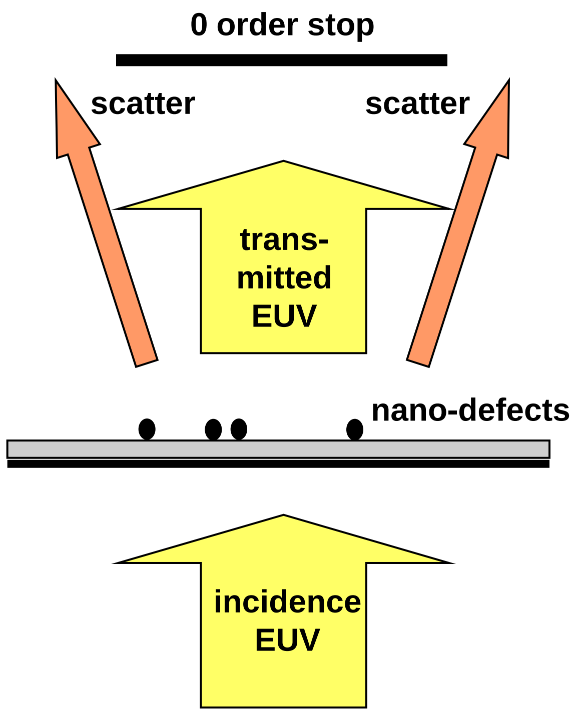
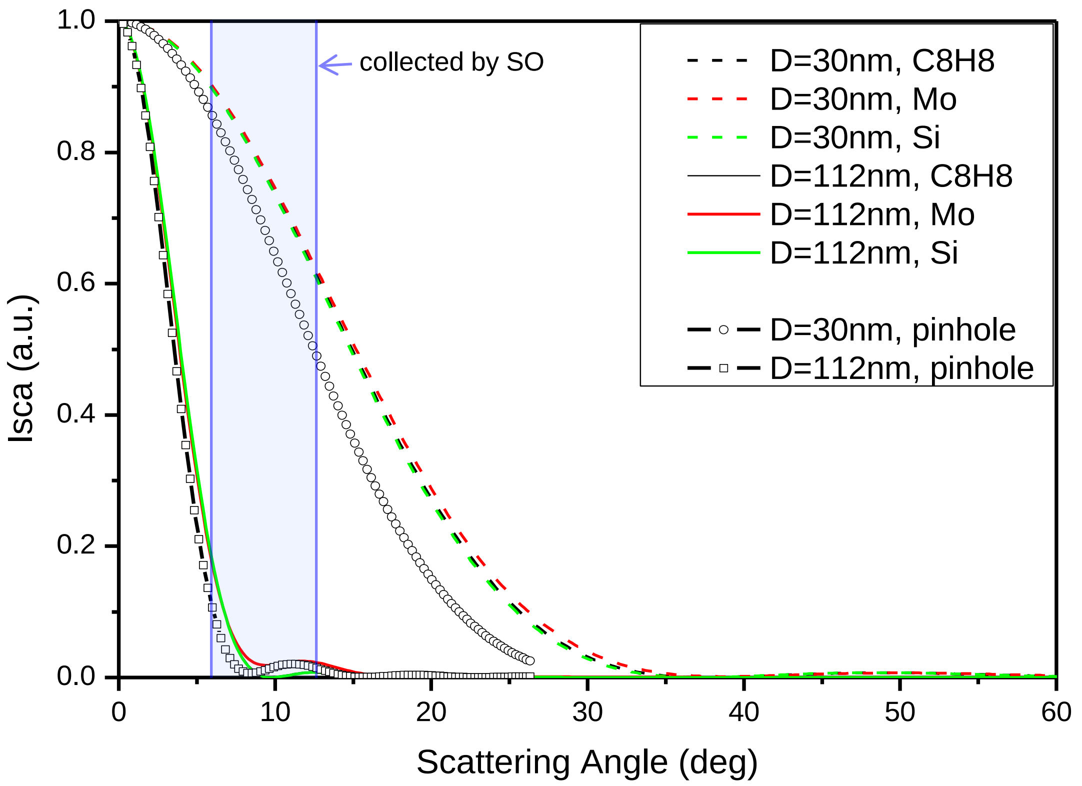
Dark field microscopy for defect inspection

Dark field operation:
sensitivity to small structures



Pinhole diffraction model and Mie scattering distribution as a function of the scattering angle for two diameters: 30 nm and 112 nm and for different materials



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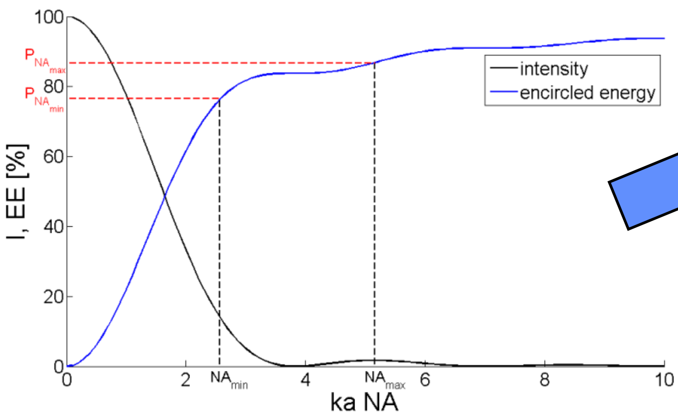
Detectable signal vs. defect size

Number of detectable photons as a function of defect size

- **pinhole approach**

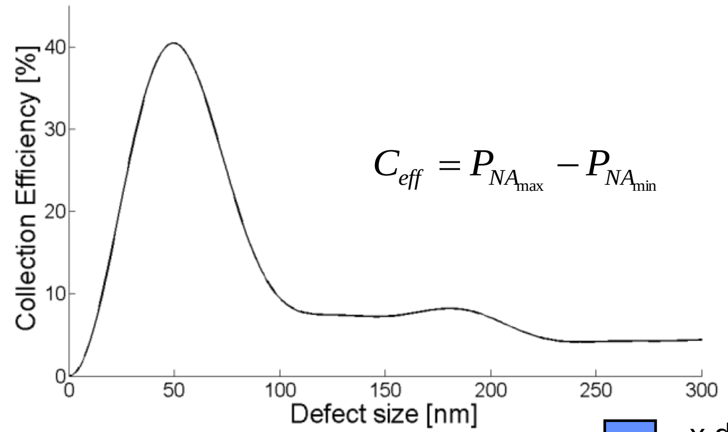


$$I(x) = \left(\frac{2 \cdot J_1(x)}{x} \right)^2$$

$$P(x) = 1 - (J_0(x))^2 - (J_1(x))^2$$

$$x = k \cdot a \cdot NA$$

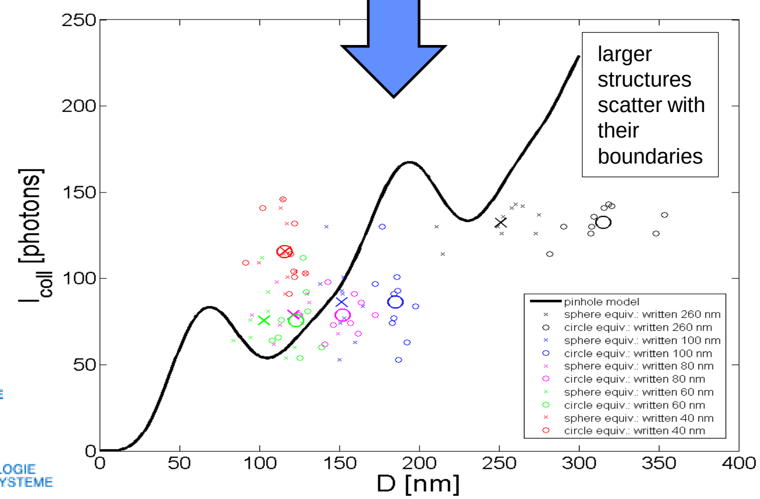
a = defect radius



$$C_{eff} = P_{NA_{max}} - P_{NA_{min}}$$

x defect area

For dose in object plane: 1.2 mJ/cm² + losses through the system ➔



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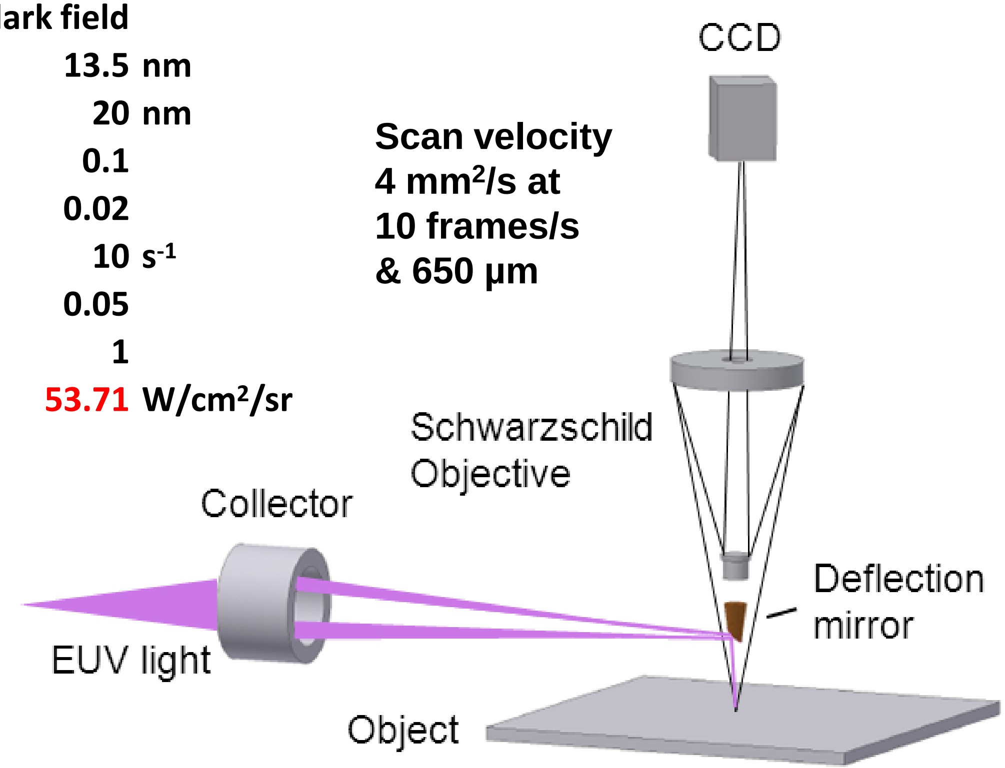
Sensitivity matched dark field microscopy (scatterometry)

$$L_{source} = \frac{25 \cdot fps \cdot h \cdot c/\lambda}{QE \cdot C_{df}^2 \cdot T_{illumination} \cdot T_{imaging} \cdot \pi \cdot NA_{illumination}^2 \cdot \int_{\Omega_{imaging}} \frac{d\sigma}{d\Omega} \cdot d\Omega}$$

probability of finding a scattered particle within a given solid angle, ~ defect area * scattering efficiency into the objective NA

	bright field	dark field	dark field	
wavelength	13.5	13.5	13.5	nm
pixel/feature size	9.15	27.45	20	nm
T feature	0.5	0.1	0.1	
T System	0.02	0.02	0.02	
fps	1	1	10	s^{-1}
NA illumination	0.3	0.1	0.05	
contrast	-0.5	1	1	
radiance	0.29	0.71	53.71	$W/cm^2/sr$

Scan velocity
$4\ mm^2/s$ at
10 frames/s
& 650 µm



Source requirements:

used etendue ~ $1 \cdot 10^{-4}\ cm^2 sr$

collection efficiency $\eta_{coll} = \Omega / 2\pi \cong 5 \cdot 10^{-3}$

average radiance ~ 0.3 – 100 $W/(cm^2 sr)$

~ 1 W/2π (DPP, 1:1 imaging)

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Summary – radiance requirements

EUV and soft x-ray microscopy enables imaging of nanometer sized object features with high analytical sensitivity, very good spatial resolution, and penetration depths compatible with relevant sample sizes.

Source radiance requirements are derived from the fundamental considerations of sample resolution, image contrast, detector quantum efficiency and throughput.

Photon counting is characterized by Poisson statistics. Requirement of being able to distinguish between (noisy) signal and (noisy) background results in inverse dependence of radiance on contrast squared.

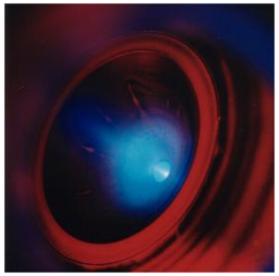
The etendue used by a high resolution EUV imaging application scales with the area of the smallest feature to be resolved or detected which is of the order of λ^2.

Taking into account conservation of etendue ("not compressibility" of light) and photon energy, the required radiance is proportional to λ^{-3}.

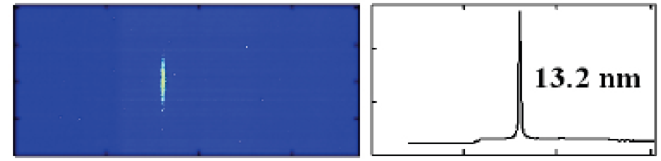
$$L_{source} = \frac{25 \cdot fps \cdot h \cdot c/\lambda}{C^2 \cdot T_{system} \cdot \pi \cdot NA^2_{illumination} \cdot A_{to\ resolve\ or\ detect}}$$

In accessing the nano-world with laboratory imaging systems, this strong dependence implies a serious challenge for the source development.

Outlook



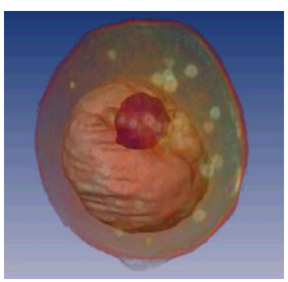
<u>XUV plasma based sources</u>
- very efficient technology
- successfully used in EUVL & metrology



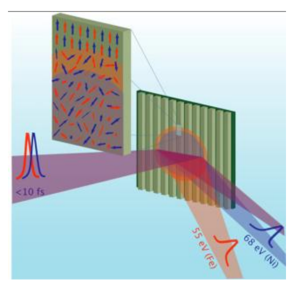
<u>High brilliance metrology sources</u>
- small emitting volume
- XUV lasers

future research challenges

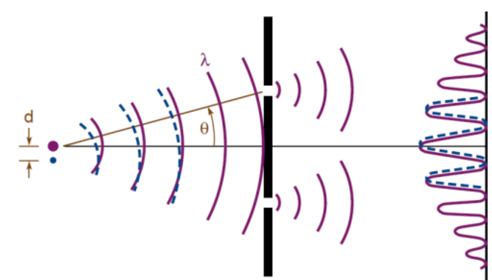
<u>3d imaging</u>
- combining of lateral and in-depth resolution
- cell nanotomography



<u>Spectro-microscopy</u>
- combining of spectral and lateral resolution
- magnetic domains



<u>Coherence</u>
- holography
- lens less imaging
- interference litho



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Thank you very much for your attention!