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Aberration retrieval for a lithographic lens in the presence of focus noise and spatial diffusion

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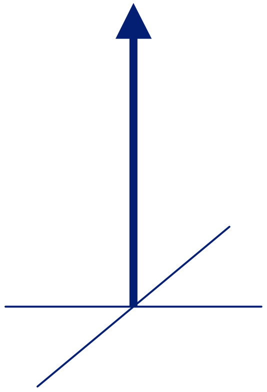
Overview

- Introduction to the Point-Spread Function and the Extended Nijboer-Zernike theory
- Retrieving aberrations
- Lithographic applications: retrieving aberrations in the presence of spatial diffusion and focus noise.
- A compact resist model: ADDIT
- Summary and references.

Point-spread function

δ - function



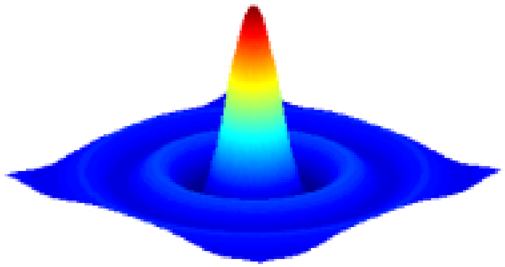
Lithographic lens,

Reticle inspection tool,

Microscopes or

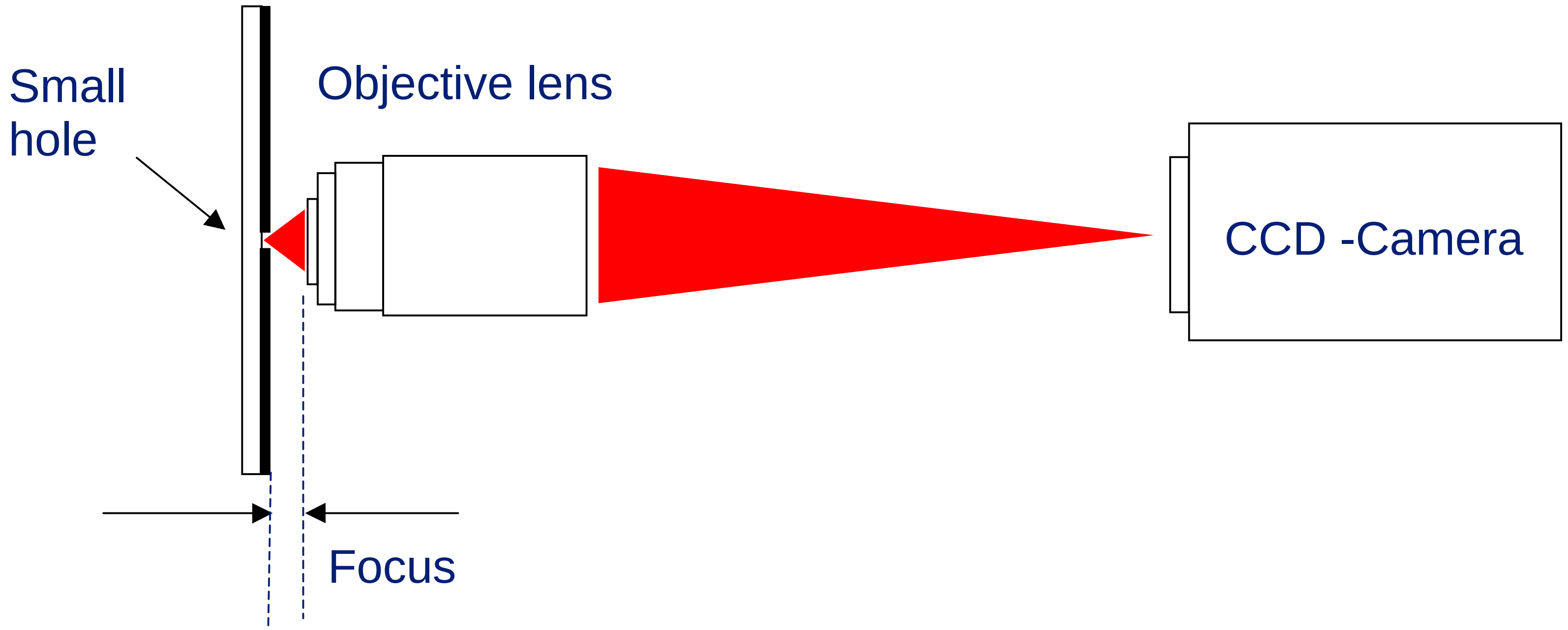
EUV Mirror system.

PSF



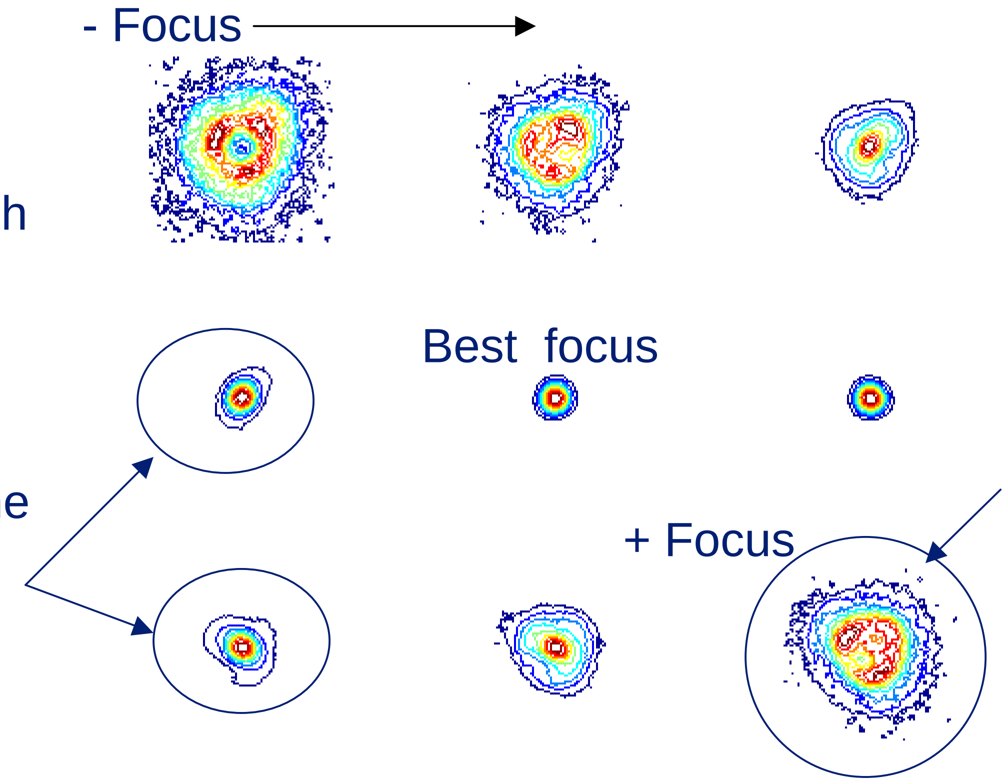
The Extended Nijboer-Zernike theory (ENZ) provides an analytical description of the PSF. The theory allows the retrieval of lens aberrations and process parameters from the measured intensity PSF.

Basic scheme for microscope



Record the through-focus intensity point-spread function.

Experimental through-focus intensity PSF

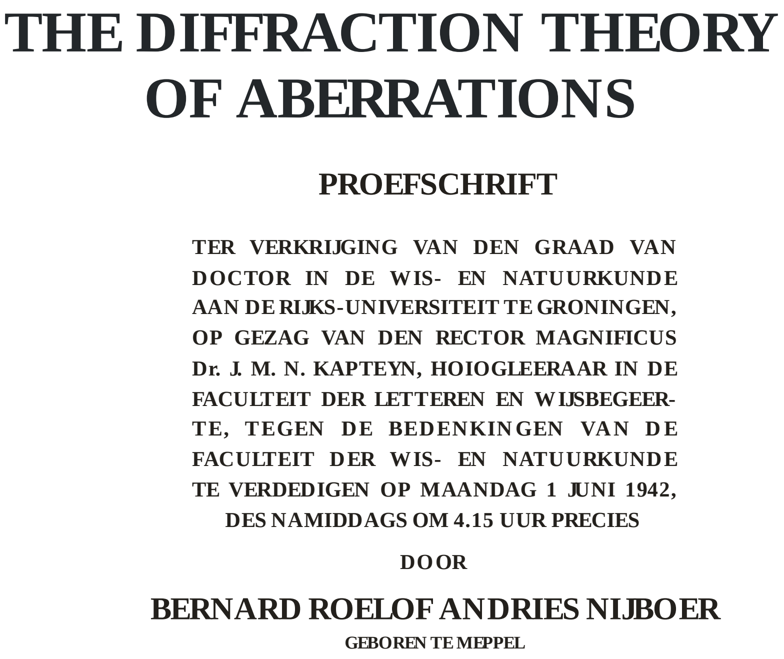


Elliptical shape that flips through focus indicates **astigmatism**. Note the ~45-degree orientation of the ellipse.

With some creating interpretation you can see a small amount of **three-foil**: a ‘triangle’ like deformation .

What aberration type, low order – high order, how many *m*λ?

For interpretation: need a diffraction theory



THE DIFFRACTION THEORY
OF ABERRATIONS

PROEFSCHRIFT

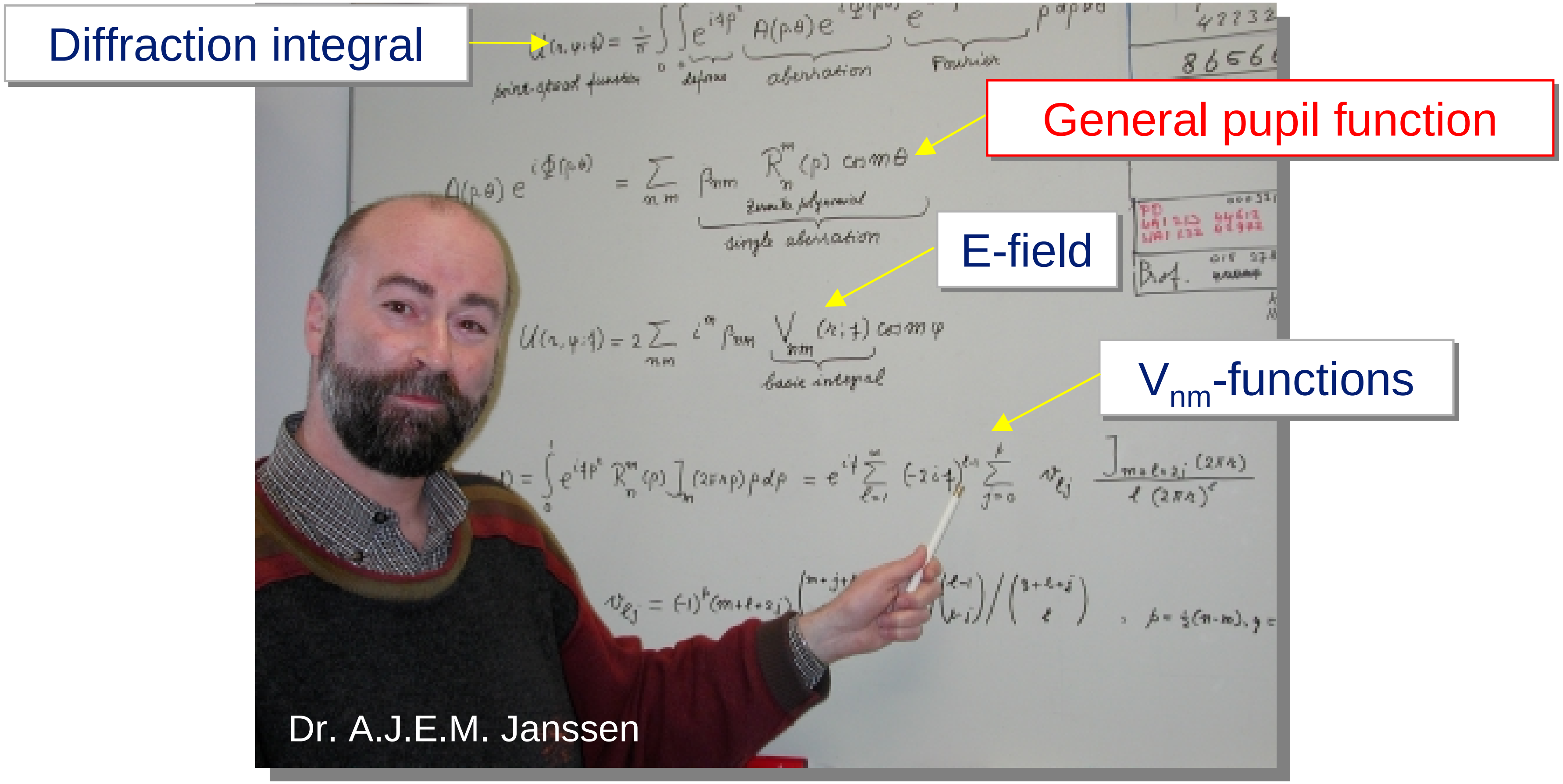
TER VERKRIJGING VAN DEN GRAAD VAN
DOCTOR IN DE WIS- EN NATUURKUNDE
AAN DE RIJKS-UNIVERSITEIT TE GRONINGEN,
OP GEZAG VAN DEN RECTOR MAGNIFICUS
Dr. J. M. N. KAPTEYN, HOIOGLEERAAR IN DE
FACULTEIT DER LETTEREN EN WIJSBEGEER-
TE, TEGEN DE BEDENKINGEN VAN DE
FACULTEIT DER WIS- EN NATUURKUNDE
TE VERDEDIGEN OP MAANDAG 1 JUNI 1942,
DES NAMIDDAGS OM 4.15 UUR PRECIES

DOOR

BERNARD ROELOF ANDRIES NIJBOER
GEBOREN TE MEPPEL

- The old diffraction theories: Airy (1835), Lommel (1885) and Nijboer (1942) give the PSF only for best focus and small aberrations
- Defocus included for a few low order terms only

ENZ theory gives an analytical description of the PSF (2000 - 2002)



Diffraction integral

General pupil function

E-field

V_{nm}-functions

Dr. A.J.E.M. Janssen

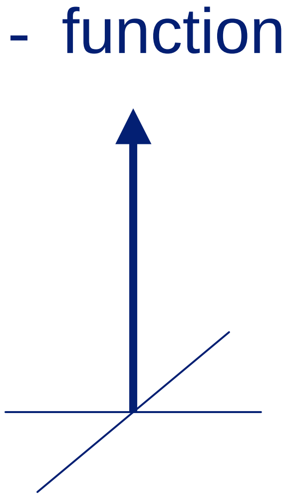
Extended Nijboer-Zernike theory

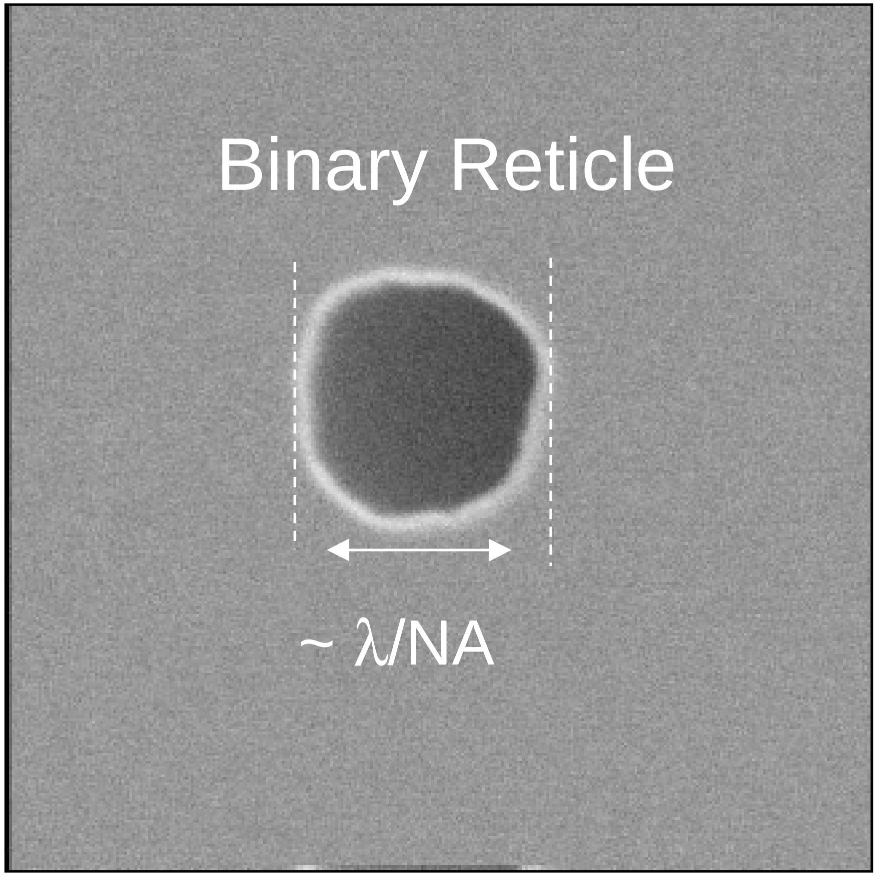
$$U(r,\varphi,f) \approx 2V_{00} + 2\sum_{nm} \alpha_{nm} i^{m+1} V_{nm} Cos(m\varphi),$$

$$V_{nm}(r,f) = \exp(if) \sum_{l=1}^{\infty} (-2if)^{l-1} \sum_{j=0}^{p} \mathrm{v}_{lj} \frac{J_{m+l+2j}(2\pi r)}{l(2\pi r)^{l}}$$

- Through-focus, symmetry, orthogonality, convergence
- Aberrations of all orders allowed
- The old theories (Airy, Lommel, and Nijboer) arise as special cases

Experimentally: the object is not a δ – function !





Take into account the finite diameter

$$U(r,\varphi,f) \quad \approx 2V_{00} + 2\sum_{nm} \alpha_{nm} i^{m+1} V_{nm} Cos(m\varphi),$$

$$V_{nm}(r,f) = \exp(if)\sum_{l=1}^{\infty}(-2if)^{l-1}\sum_{j=0}^{p} \mathrm{v}_{lj}\,\frac{J_{m+l+2j}(2\pi r)}{l(2\pi r)^{l}}$$

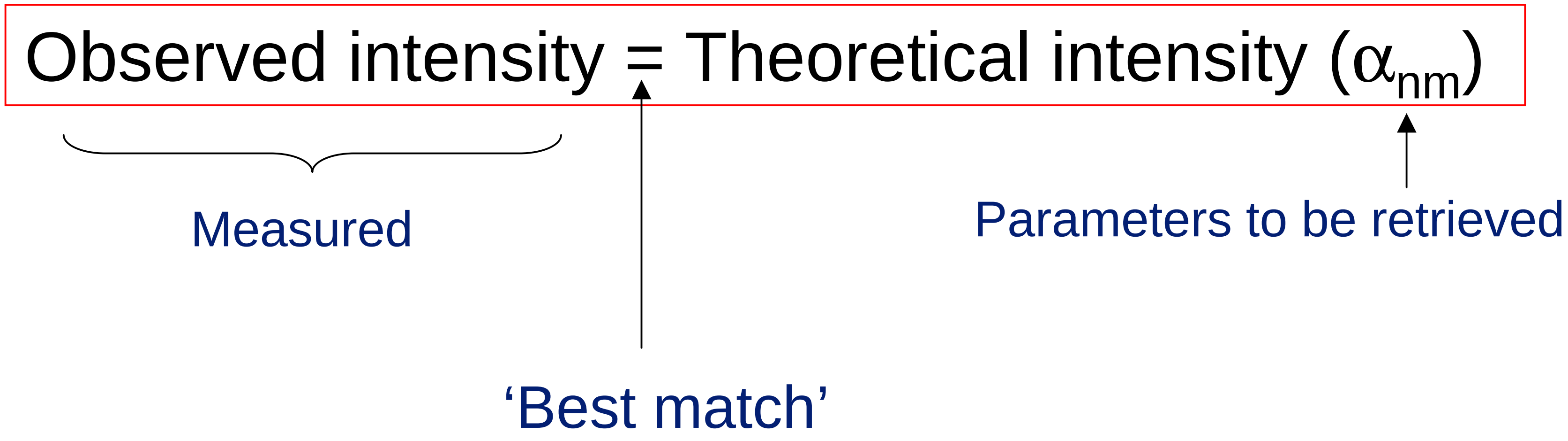
Brute force: integrate PSF over the finite hole diameter.

Better: use complex focus parameter

$$f \rightarrow f + \boxed{i.d} \longleftarrow d = \text{‘diameter’}$$

Aberration retrieval

The lens aberrations are obtained from the through-focus point-spread function.



Observed intensity = Theoretical intensity (α_{nm})

Measured

Parameters to be retrieved

'Best match'

Aberration retrieval

$$U(r,\varphi,f) \approx 2V_{00} + 2\sum_{nm} \alpha_{nm} i^{m+1} V_{nm} Cos(m\varphi),$$

$$\mathrm{I}(\mathrm{r},\varphi,\mathrm{f}) \approx 4\left|\mathrm{V}_{00}\right|^2 + 8\sum_{nm} \alpha_{nm} \,\mathrm{Re}\left\{i^{m+1} V_{00}^{*} V_{nm}\right\} Cos(m\varphi) + \ldots$$

Drops out !

$$\psi^{m} = m^{th} - \text{Fourier component of } I(\mathrm{r},\varphi,\mathrm{f})$$

$$\psi^{m} = \sum_{n} \alpha_{nm} \psi_{n}^{m} \quad \text{with} \quad \psi_{n}^{m} = 4\,\mathrm{Re}\left\{i^{m+1} V_{00}^{*} V_{nm}\right\}$$

Take inner products :

$$(\psi^{m}, \psi_{n'}^{m}) = \sum_{\mathrm{n}} \alpha_{\mathrm{nm}} (\psi_{n}^{m}, \psi_{n'}^{m}) \longrightarrow$$ a linear system of equations.

Aberration retrieval & noise

m^{th} - Fourier component

basic intensity functions

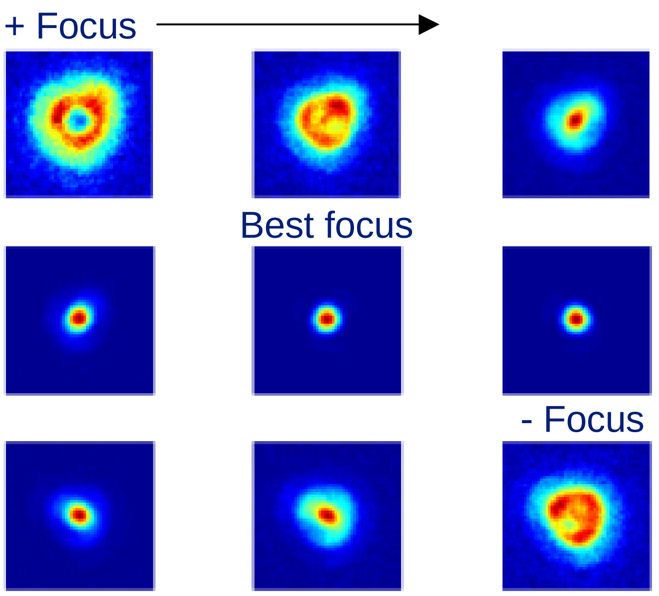
$$\psi^m = \sum_n \alpha_{nm} \psi_n^m \quad \text{with} \quad \psi_n^m = 4\,\mathrm{Re}\left\{ i^{m+1} V_{00}^* V_{nm} \right\}$$

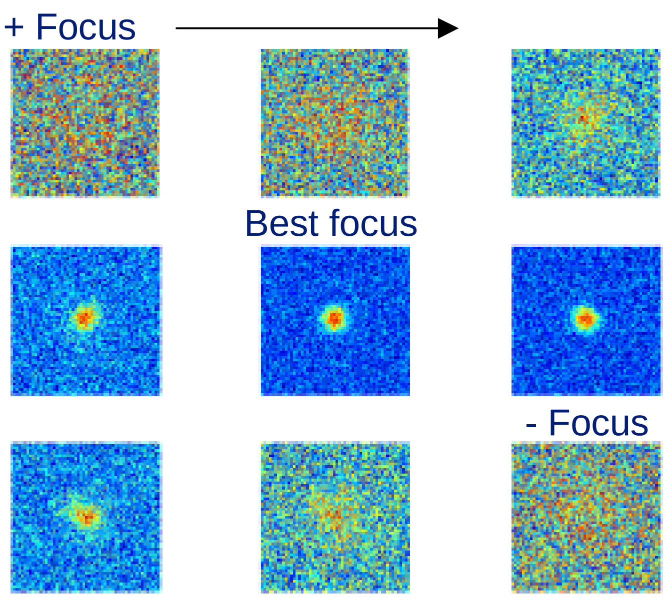
Aberration parameter

Match experimental frequency component (ψ^m) to specific through-focus signatures ($\psi^m{}_n$). The $\psi^m{}_n$ are (close to being) orthogonal.

- Aberration retrieval is *noise insensitive*
- Be careful with DC-intensity offset

Example: impact noise



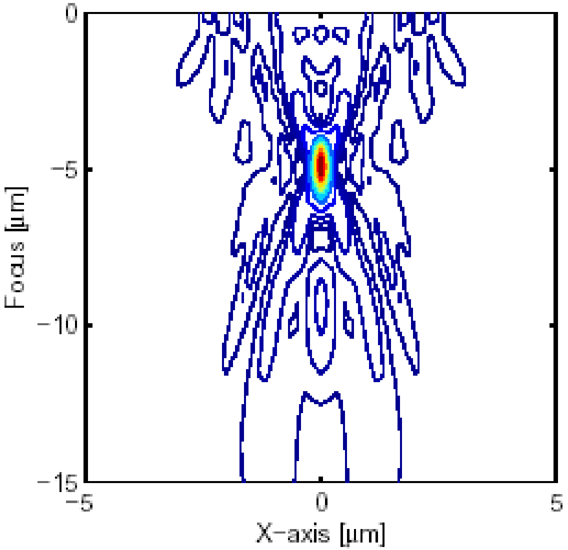


Small change in retrieved aberration coefficients: $\Delta Z \sim 10\ m\lambda$

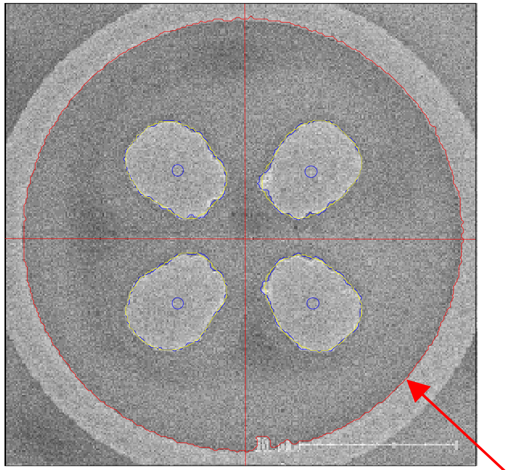
Generalizations ENZ theory

Various generalizations of the ENZ-theory exist. In addition to finite hole size: phase and transmission errors, large aberrations, large defocus.

Example: ENZ - large defocus used to simulate the imaging properties of a Fresnel zone-lens for a DUV stepper (λ=0.248, NA =0.60)



Lithographic application: source metrology. Example: the image in resist of a quadruple source observed by an SEM.



NA - lens

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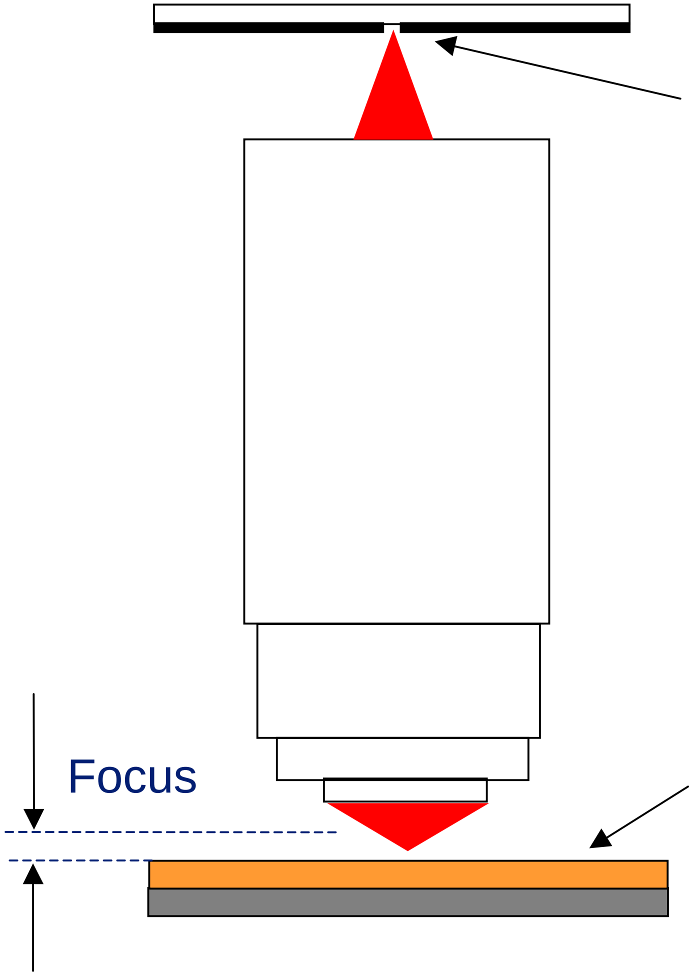
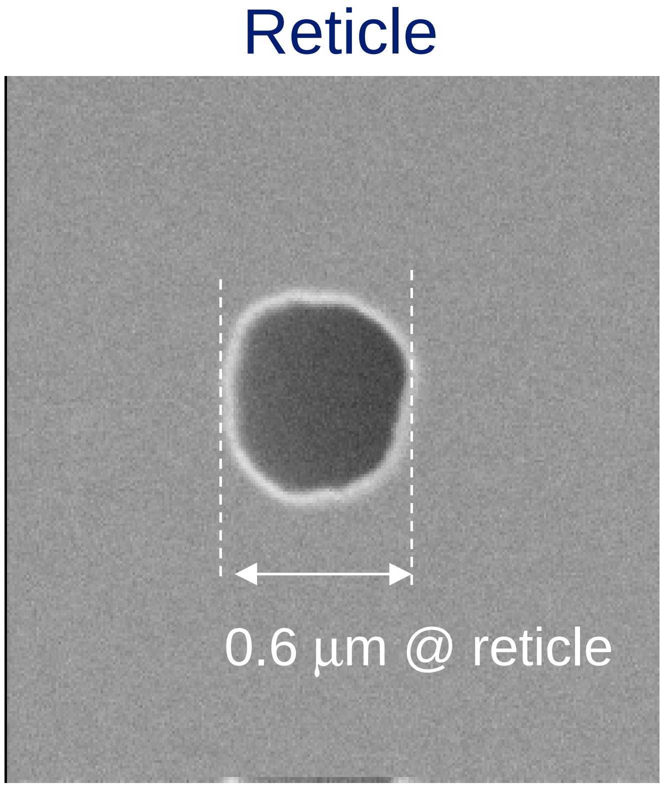
Basic scheme for scanner

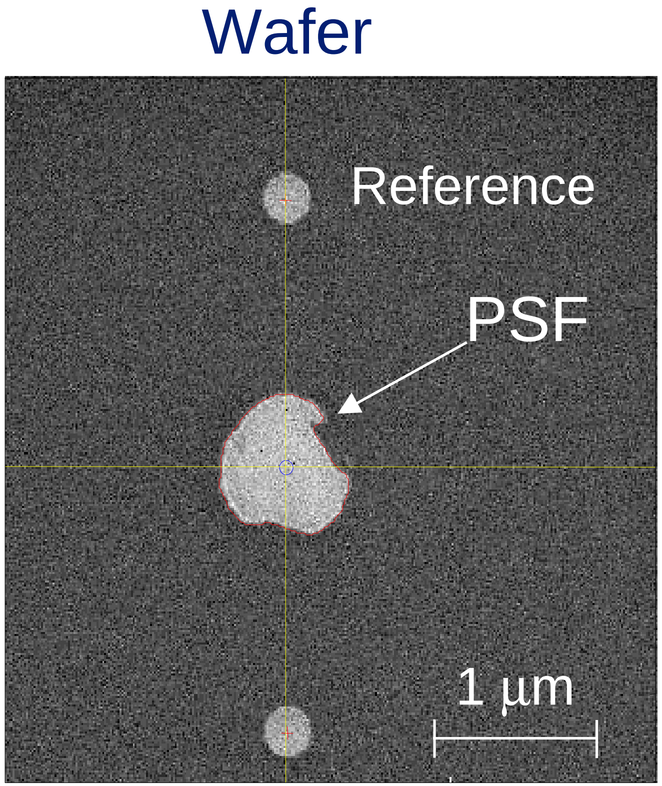


Compared to a microscope:

- Record in photo-resist: interpret SEM-images
- Resist baking and development process
- Chromatic aberrations

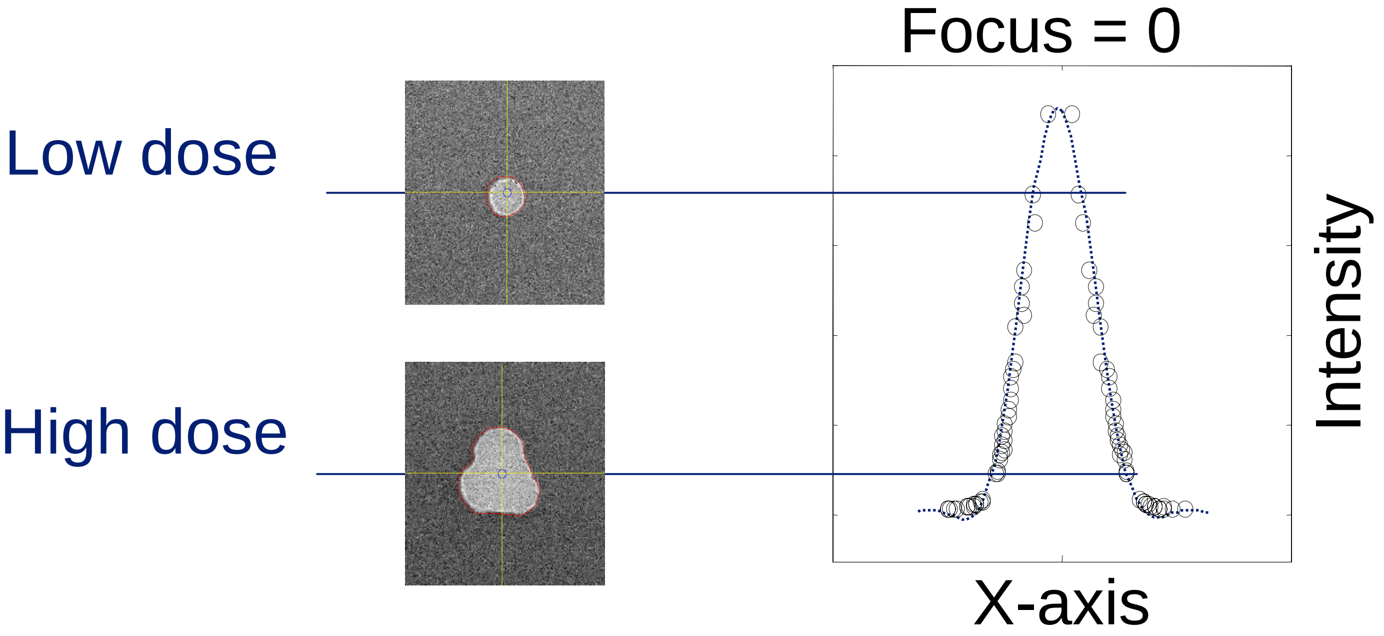
Record images in photo resist





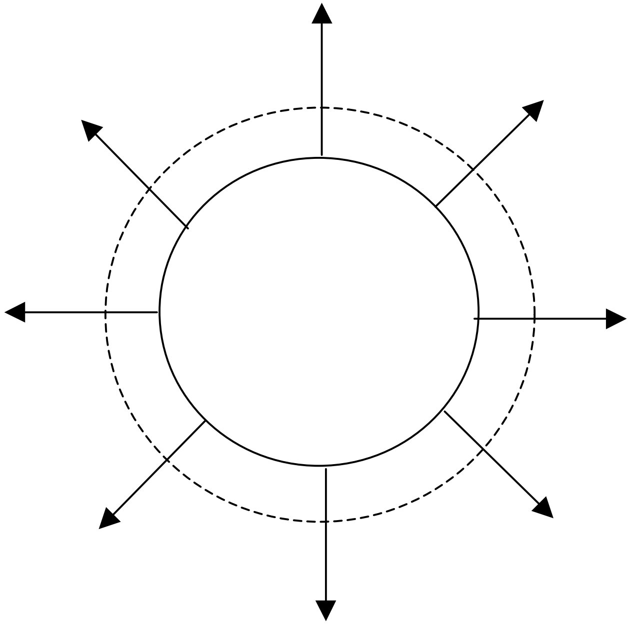
One exposure: single contour point-spread function

Contours to Intensity PSF



The through-focus intensity PSF is constructed from one focus-exposure matrix (FEM) of an isolated contact hole.

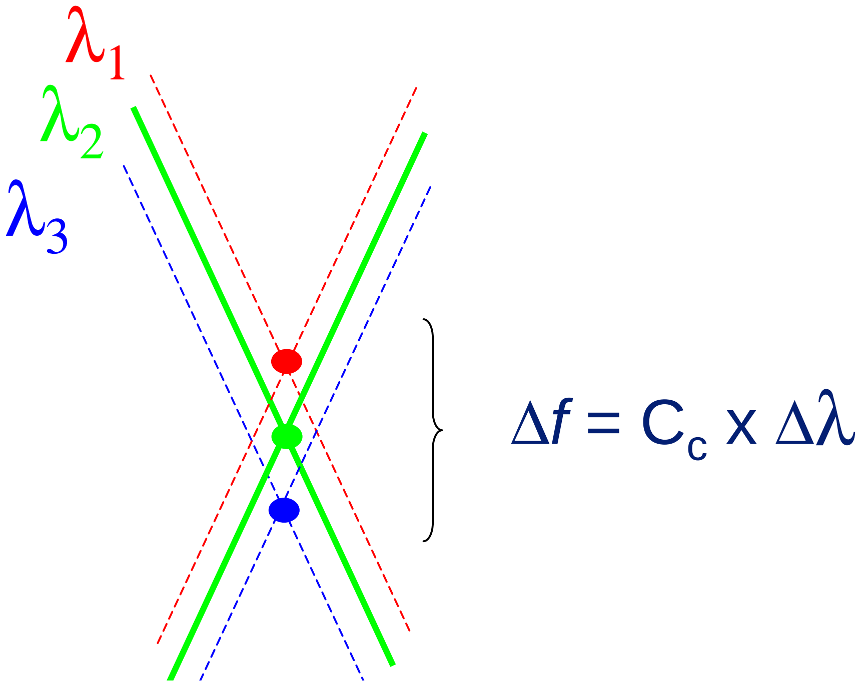
Diffusion



During the baking, a diffusion process takes place, that *increases* the diameter of the PSF.

The ENZ approach can take diffusion into account.

Chromatic aberrations



$\Delta f = C_c \times \Delta\lambda$

Chromatic aberrations and finite laser-bandwidth cause image blur along the focal axis: the observed depth of focus (DOF) is *increased*.

The ENZ approach can take focus noise into account.

More generalizations ENZ theory

- ♦ Retrieval of diffusion, chromatic aberrations,

(The extension to the full vectorial high-NA ENZ-theory is presented by J.J.M. Braat, see the next presentation)

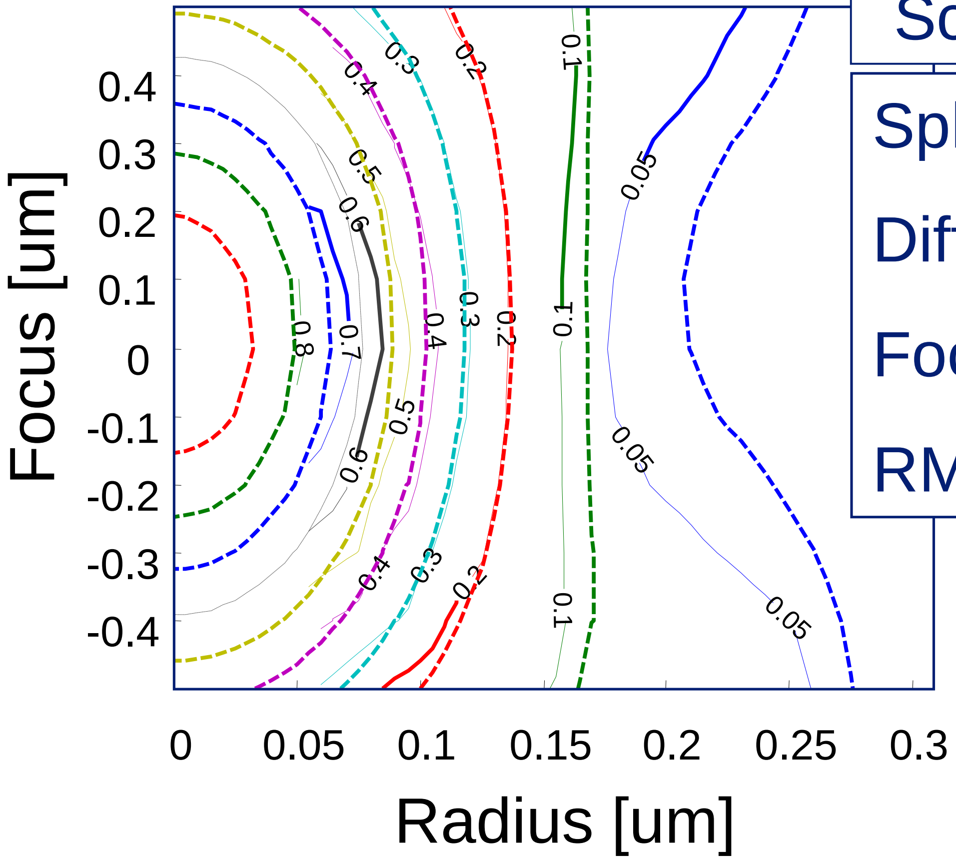
$$I(r,f) \approx \sum_j Z_j[\text{Aerial image}] + \sigma_R^2[\text{Diffusion}] + \sigma_F^2[\text{Focus noise}],$$

$$\text{Aerial image} : V_{n,m}V_{0,0}^{*} \longleftarrow$$ see page 12

$$\left.\begin{array}{ll} \text{Diffusion} & : \\ \text{Focus noise} & : \end{array}\right\}$$ Explicit functions in terms of $V_{n,m}$

- ♦ Aerial image, diffusion and focus noise - basic intensity functions are known functions with specific fingerprint.

Parameter extraction: best match

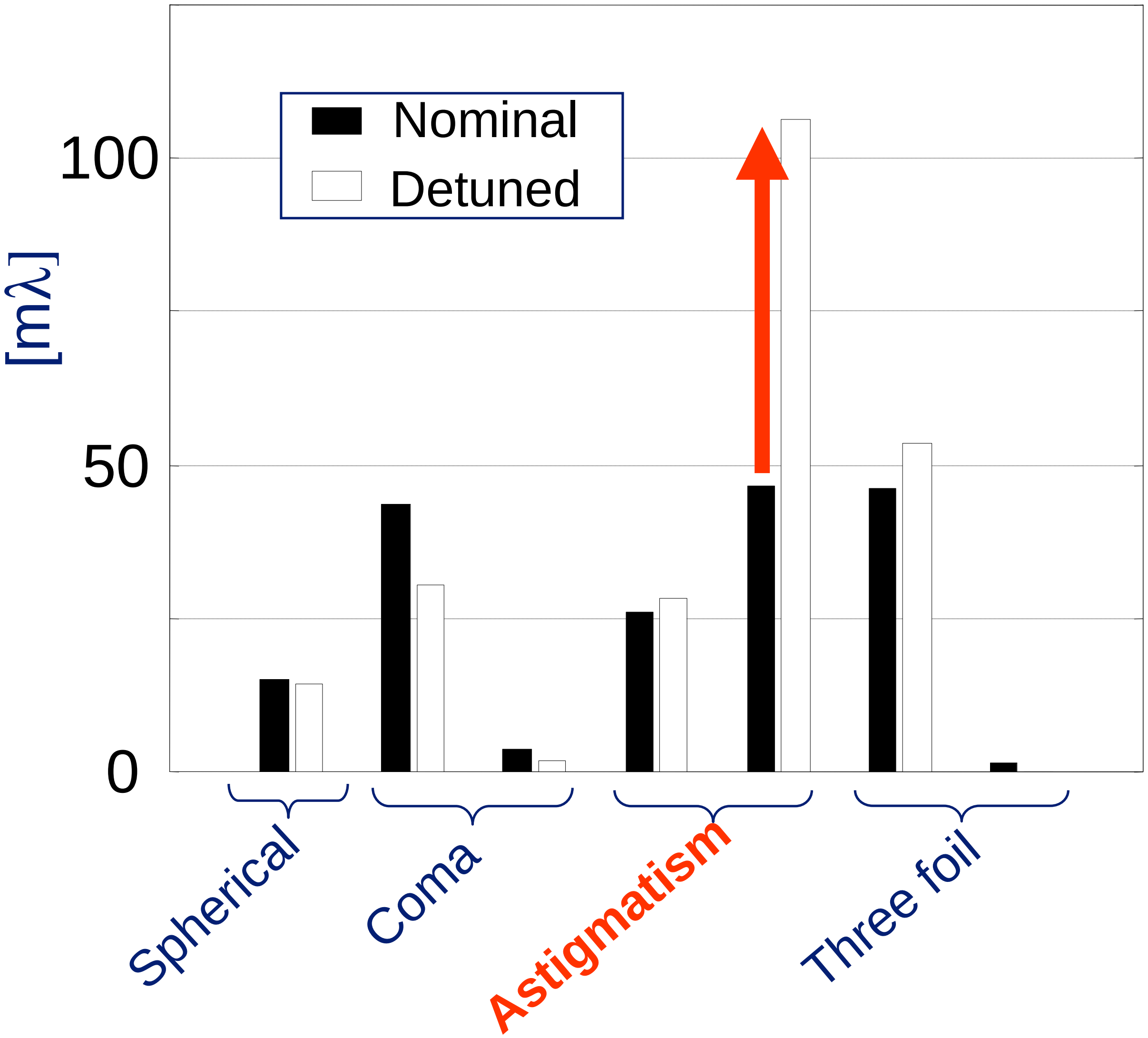


Scanner: NA=0.63, λ=193 nm

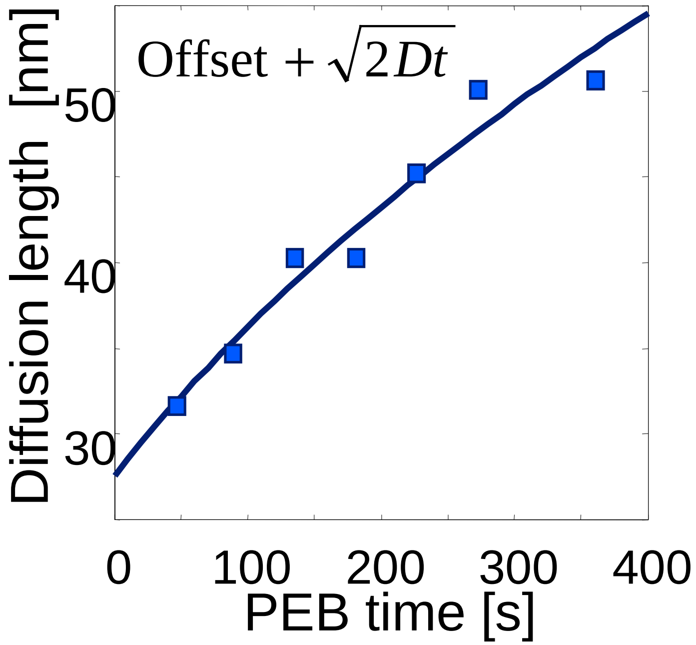
Spherical	= 34 mλ
Diffusion	= 31 nm
Focus noise	= 195 nm

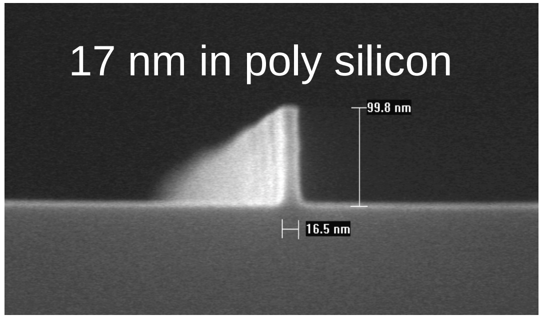
RMS fit error 1.5 % typical

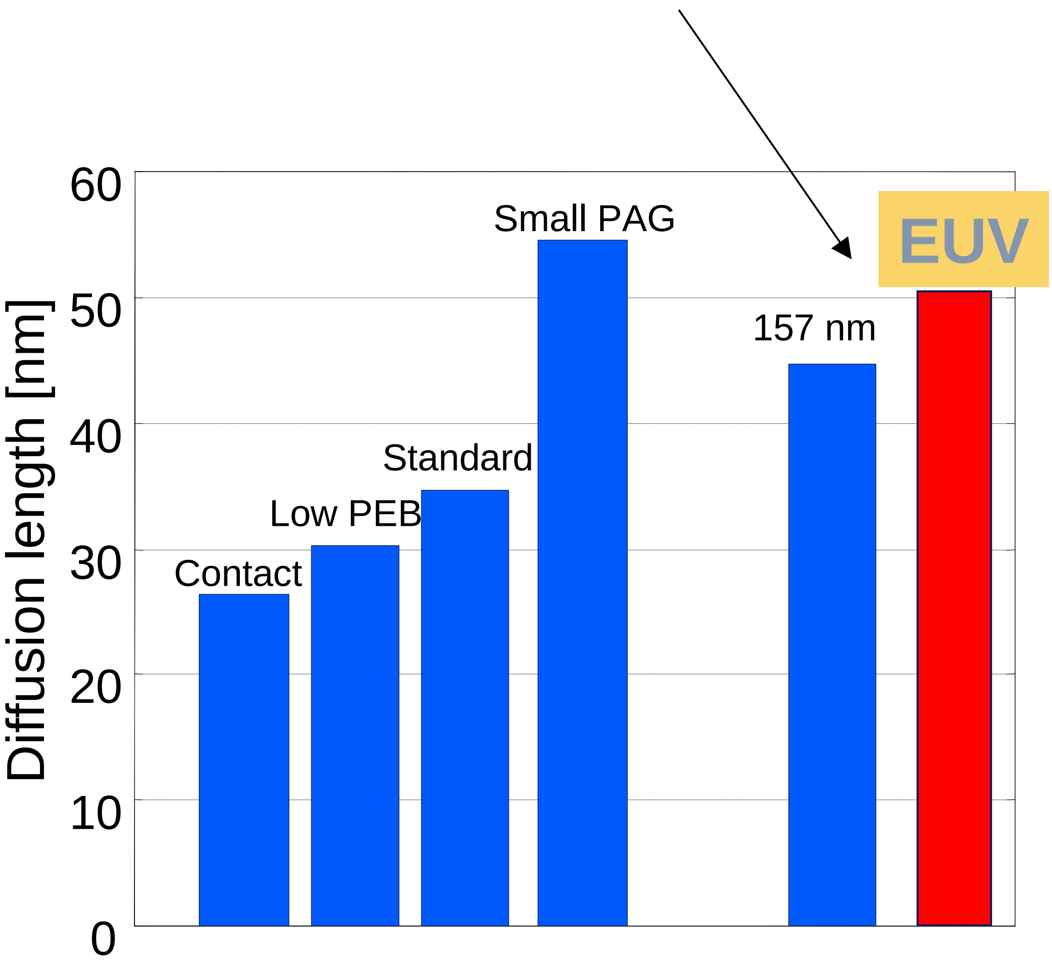
Aberrations



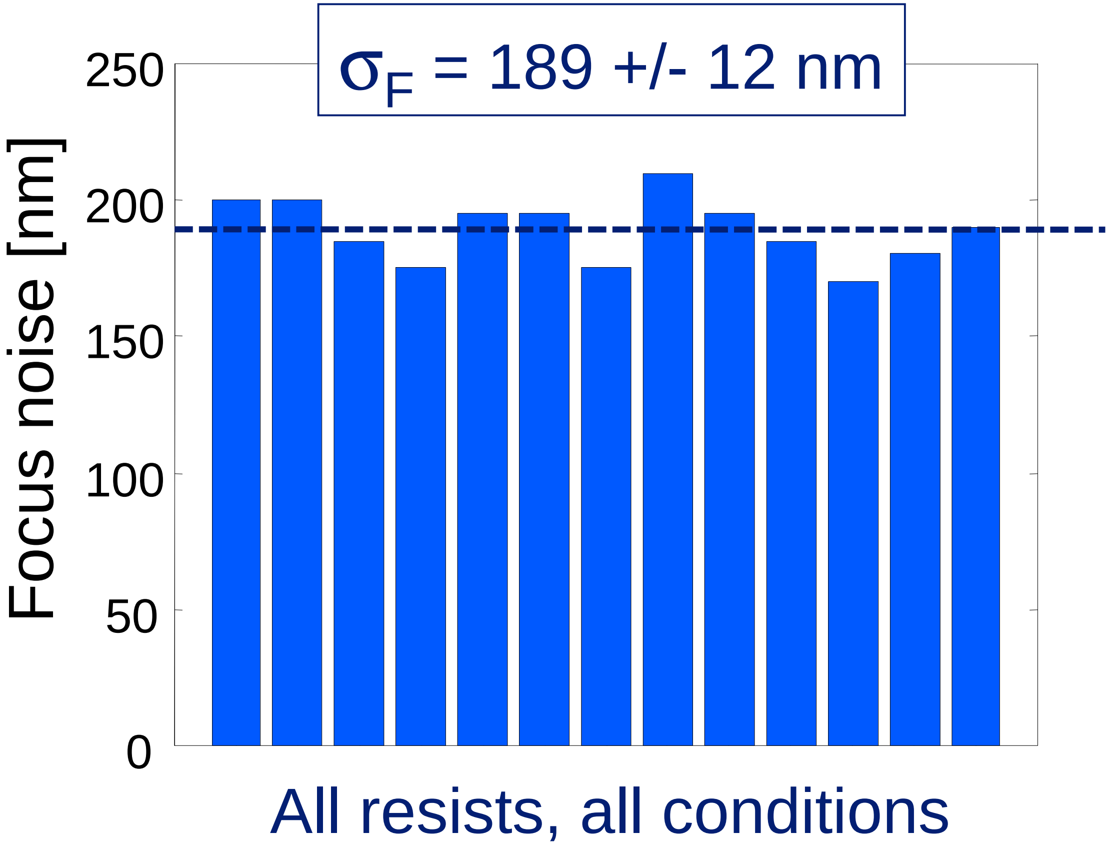
Diffusion


$\text{Offset} + \sqrt{2Dt}$
Diffusion length [nm]
30
40
50
0
100
200
300
400
PEB time [s]


17 nm in poly silicon
99.8 nm
16.5 nm


Large !
EUV
157 nm
Small PAG
Standard
Low PEB
Contact
Diffusion length [nm]
0
10
20
30
40
50
60

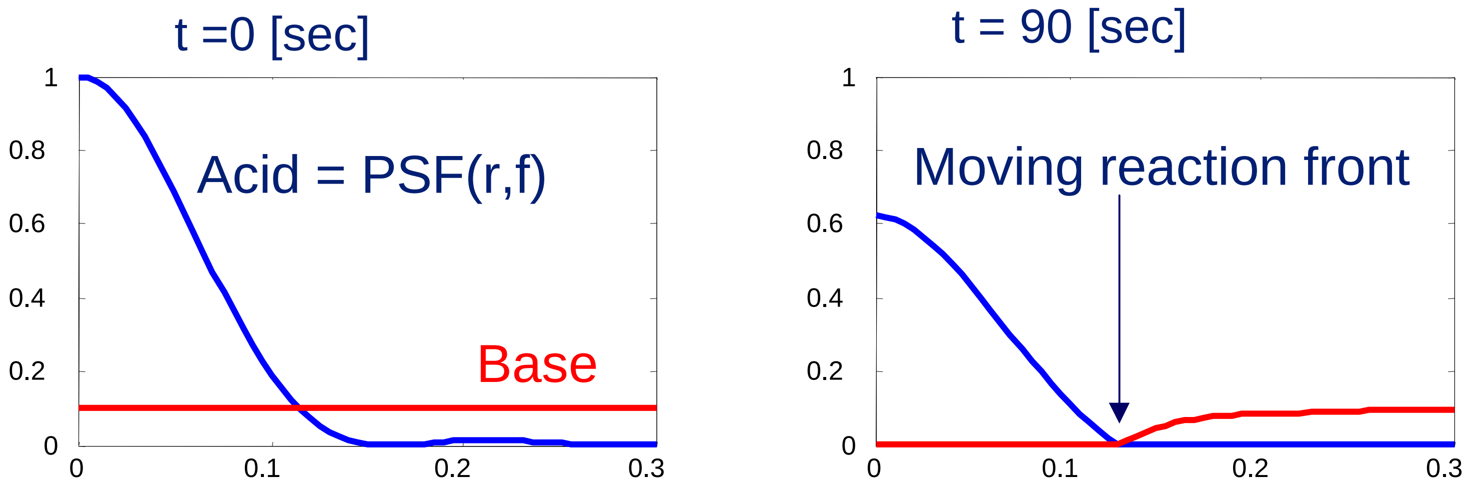
Chromatic aberrations



Correlates to laser bandwidth and chromatic aberrations projection lens

Extended Nijboer-Zernike and ADDIT

- ADDIT is a compact resist model (Lammers, 2002)
- Acid diffusion + base diffusion + chemical reaction
- Example forward calculation



- Outlook: retrieval ADDIT parameters

Summary

- Presented a method for tool and process characterization in a single experiment.
- The *inverse problem, getting the Zernike's, diffusion and focus-noise parameters, is solved* by using the extended Nijboer-Zernike approach
- Feature: clear separation between the optical parameters (pattern size, illuminator, projection lens aberrations) on the one hand and process parameters on the other.

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