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

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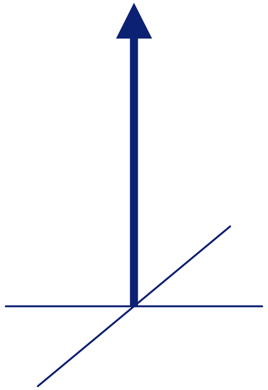
Overview

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

Point spread function

δ - function



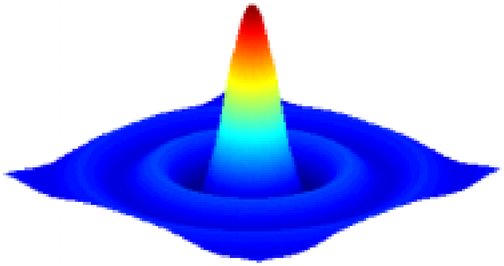
Lithographic lens,

Reticle inspection tool,

Microscopes or

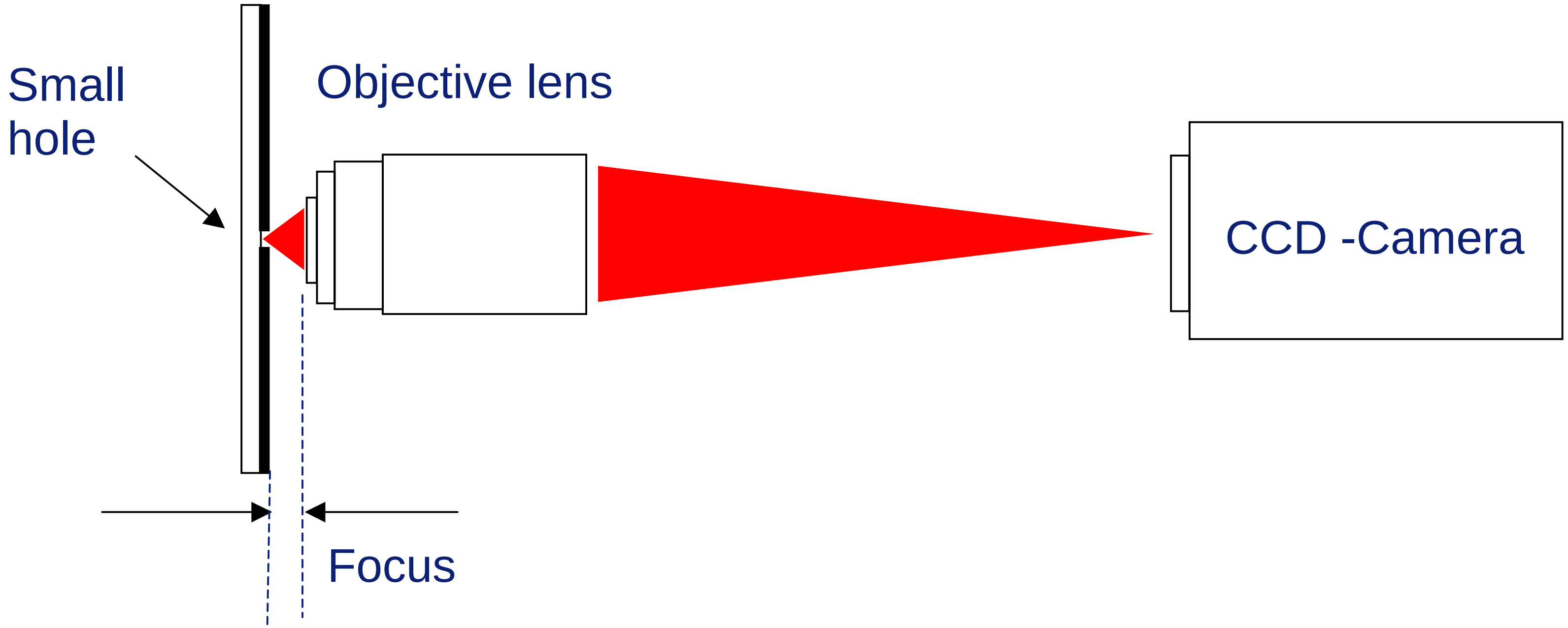
EUV Mirror system.

PSF



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

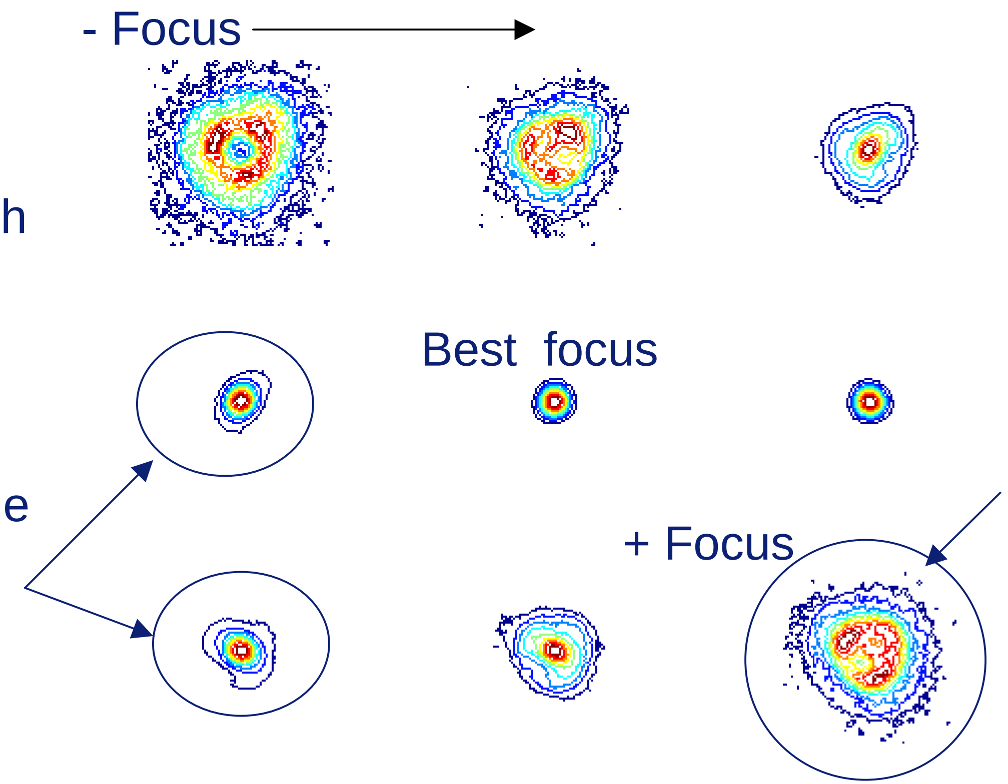
Basis schema for microscope



Record the through-focus intensity point-spread function

Experimental through-focus PSF

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



- Focus

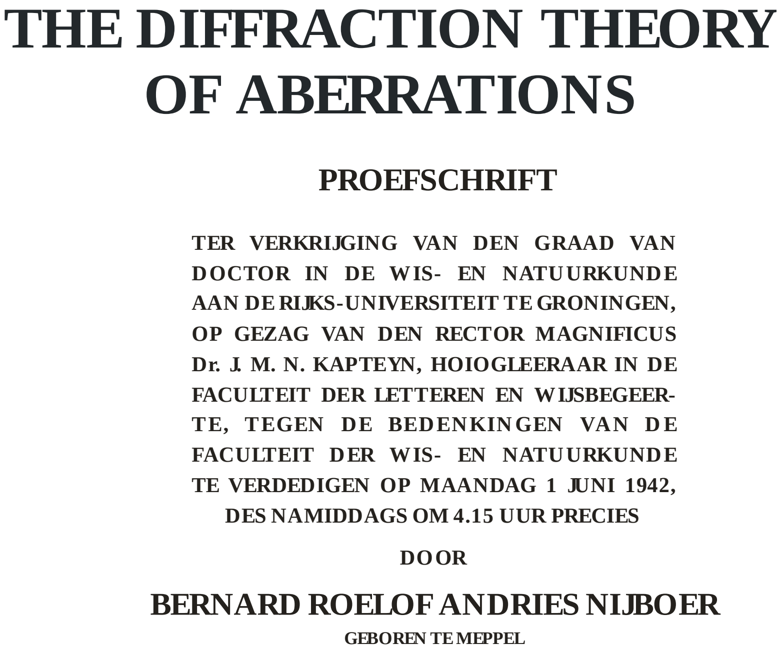
Best focus

+ Focus

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

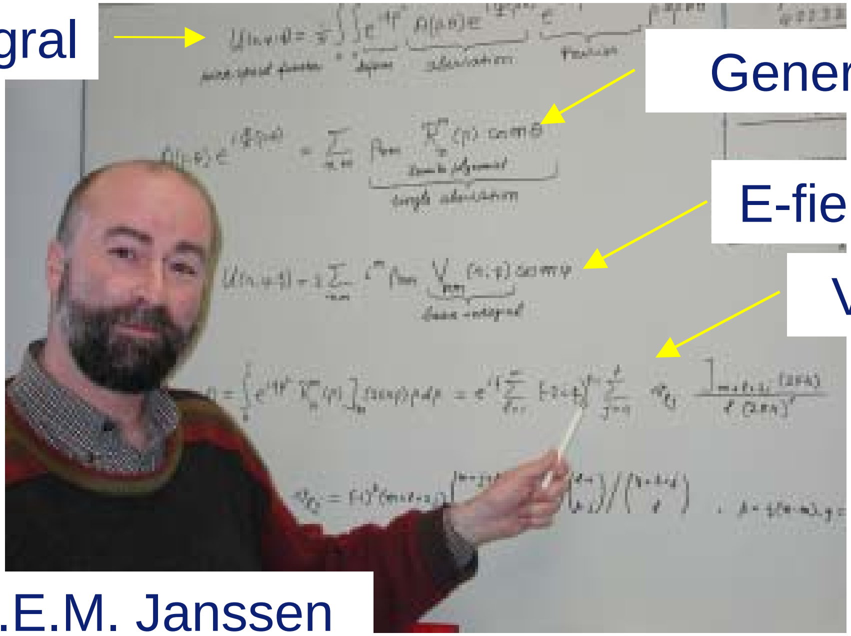
TER VERKRIJGING VAN DEN GRAAD VAN DOCTOR IN DE WIS- EN NATUURKUNDE AAN DE RIJKS-UNIVERSITEIT TE GRONINGEN, OP GEZAG VAN DEN RECTOR MAGNIFICUS Dr. J. M. N. KAPTEYN, HOIOGLEERAAR IN DE FACULTEIT DER LETTEREN EN WIJSBEGEERTE, TEGEN DE BEDENKINGEN VAN DE FACULTEIT DER WIS- EN NATUURKUNDE TE VERDEDIGEN OP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

DOOR

BERNARD ROELOF ANDRIES NIJBOER
GEBOREN TE MEPPEL

The old diffraction theories of Airy (1835), Lommel (1885) and Nijboer (1942) arise as special cases of the *Extended Nijboer-Zernike (ENZ) theory (Janssen, 2000-2002)*

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



Diffraction integral

General pupil function

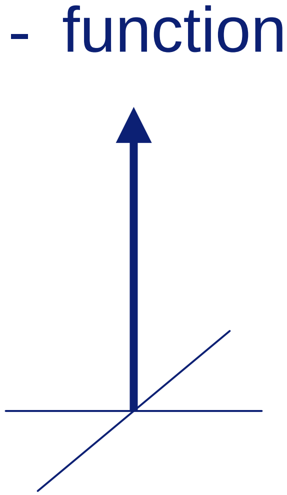
E-field

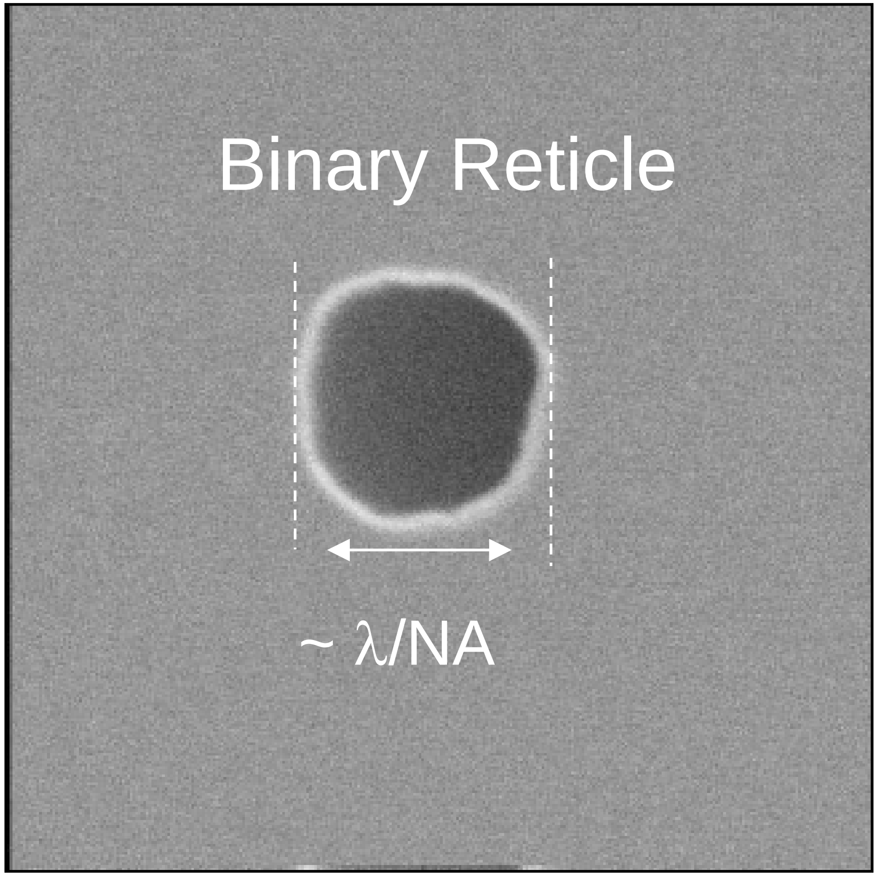
V_{nm}-functions

Dr. A.J.E.M. Janssen

- ♦ Through-focus PSF
- ♦ Aberrations of all orders allowed

Experimentally: the object is not a δ – function !





Take into account the finite diameter:

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

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

Brute force: integrate PSF over the finite hole diameter.

Better: use complex focus parameter

$$f \to f + \boxed{i.d} \longleftarrow d = \text{diameter}$$

Aberration retrieval

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

$$\boxed{\underbrace{\text{Observed intensity}}_{\text{Measured}} = \sum \underset{\substack{\uparrow\\ \text{Parameters to be retrieved}}}{\alpha_{nm}} \underbrace{\text{Basic-functions}(V_{nm})}_{\text{Calculated from theory}}}$$

Aberration retrieval

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

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

Drops out !

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

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

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

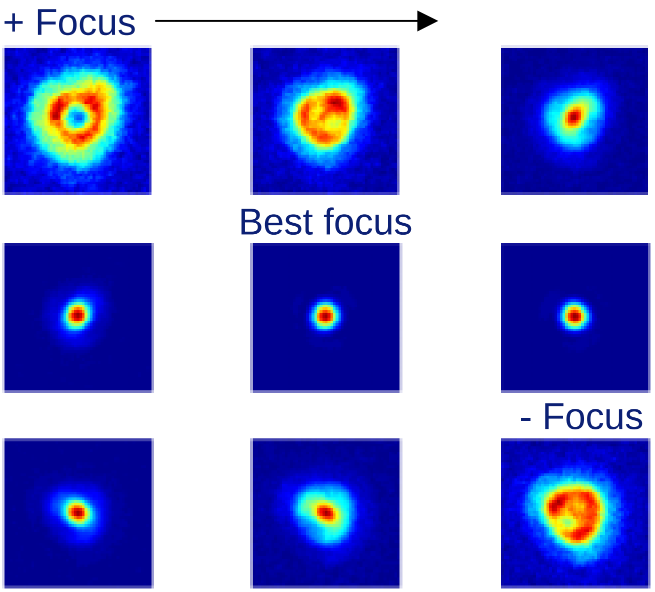
$$\psi^m = \sum_n \alpha_{nm}\psi_n^m \quad \text{with} \quad \psi_n^m = 4\,\mathrm{Re}\left\{ i^{m+1} V_{00}^* V_{nm} \right\}$$

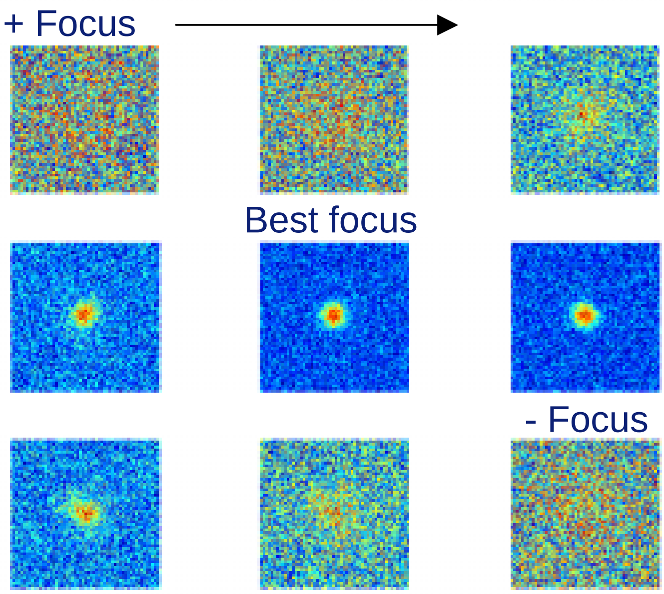
Aberration parameter

Match experimental frequency component (ψ^m) to specific through-focus signatures ($\psi^m{}_n$). Only that part of the signal that matches the signature, contributes to parameter value:

- Noise insensitive
- Be careful with DC-intensity offset

Example: impact noise





Best focus signal

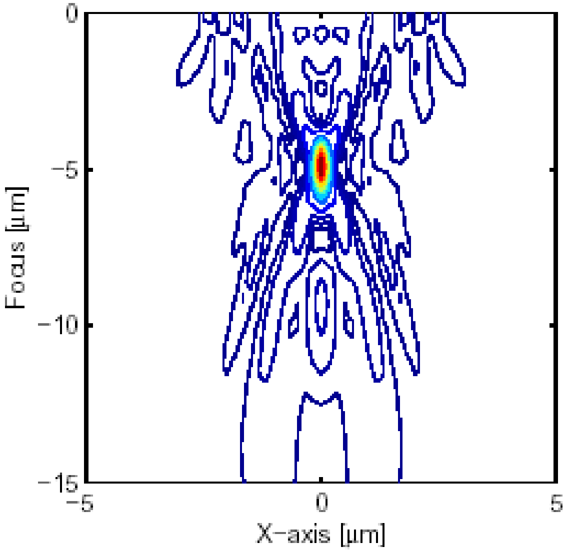
Noise level: > 150 x

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

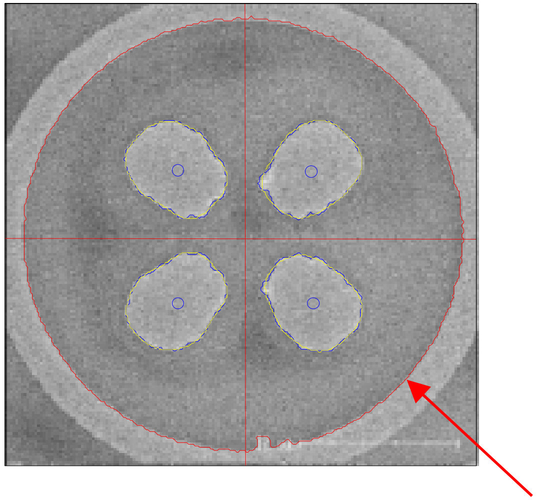
Generalizations ENZ theory

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)



Application: source metrology.
Example: quadruple source



NA - lens

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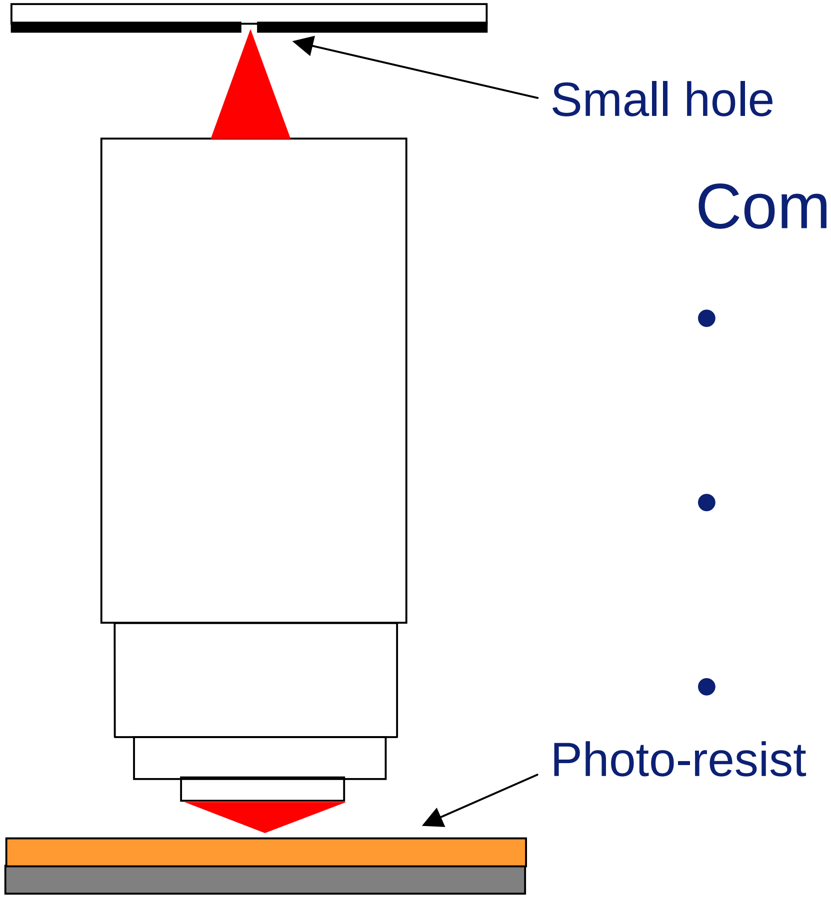
Basic scheme for scanner

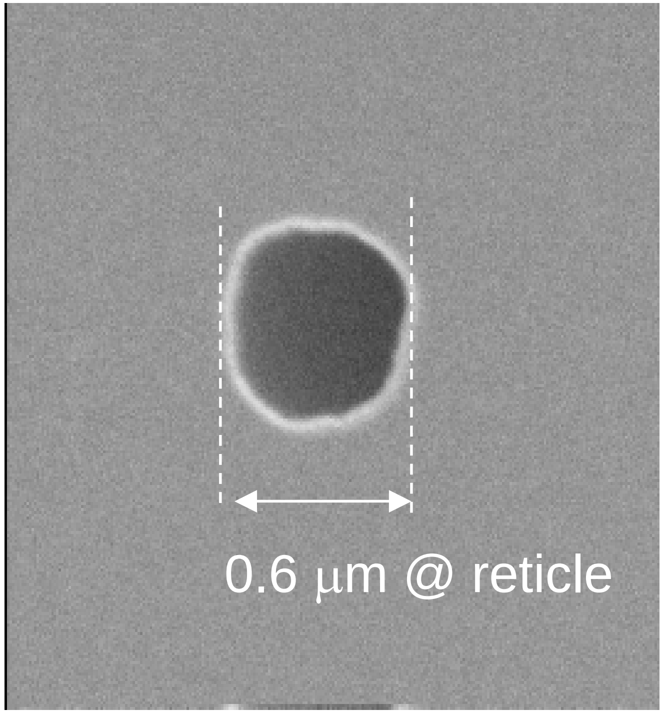


Compared to a microscope:

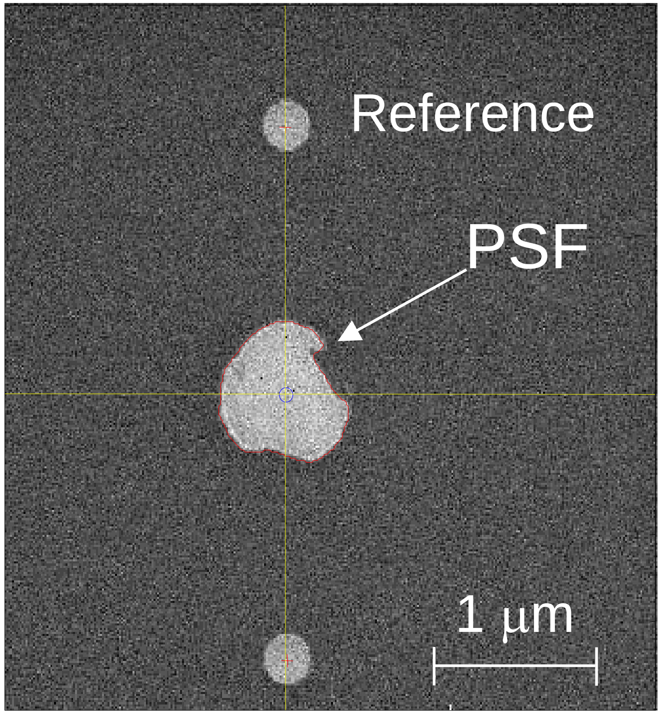
- Record in photo-resist: interpret SEM-images
- Resist baking and development process
- Chromatic aberrations

Record images in photo resist

Reticle

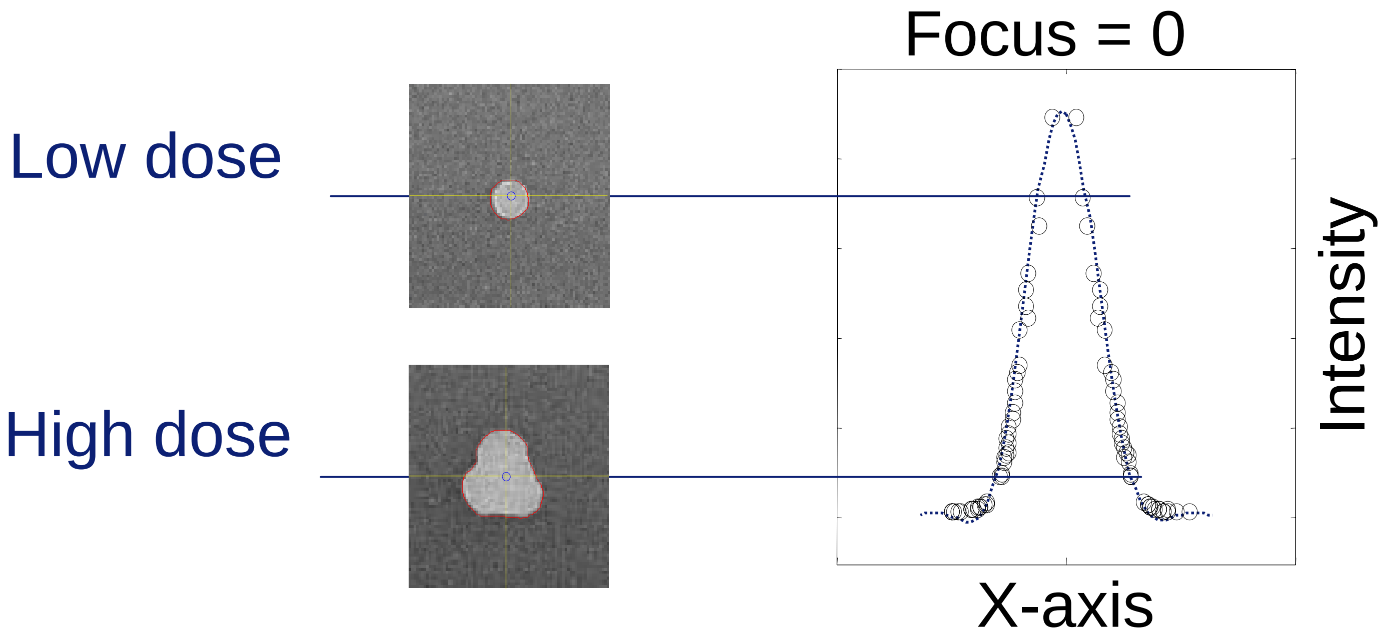


Wafer



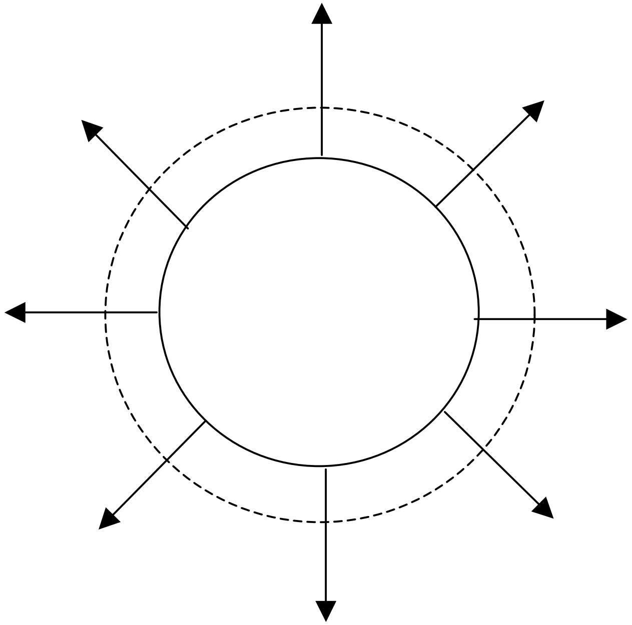
One exposure: single contour point-spread function

Contours to Intensity PSF



The through-focus PSF is constructed from a focus-exposure matrix (FEM).

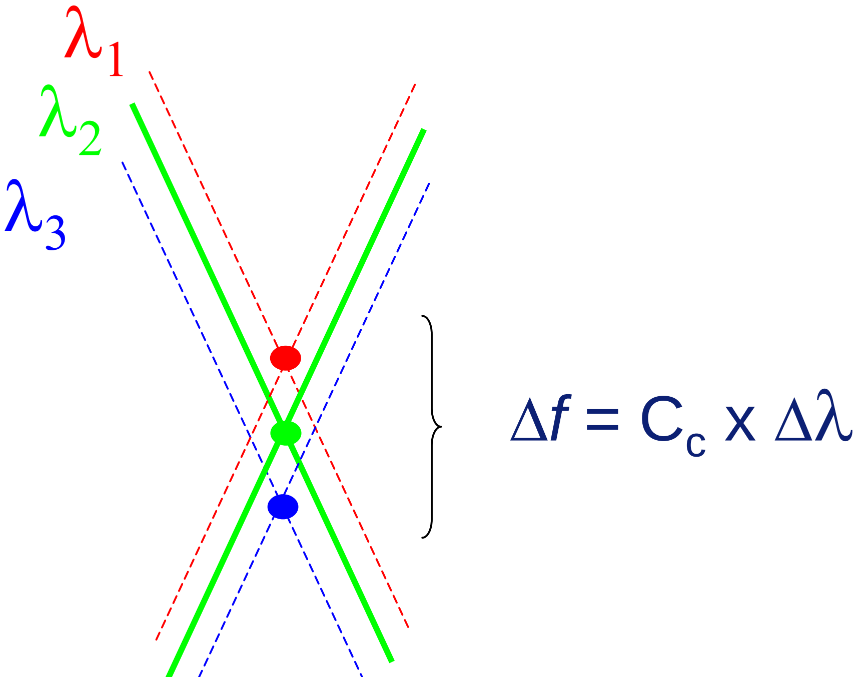
Diffusion



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,
  (full vectorial-high NA, see presentation J.J.M. Braat)

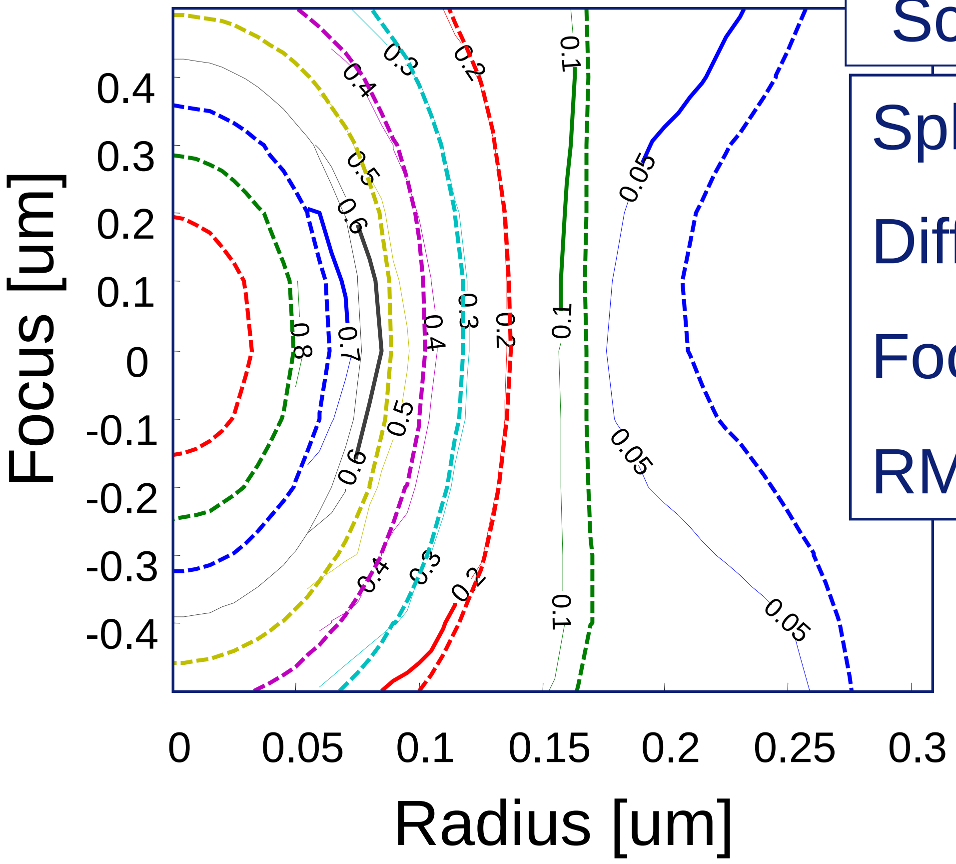
$$I(r,f) \approx \sum_j Z_j[\text{Aerial image}] + \sigma_R^2[\text{Diffusion}] + \sigma_F^2[\text{Focus noise}],$$

$$\text{Aerial image} \quad : V_{n,m}V_{0,0}^{*} \longleftarrow$$ see page 11.

$$\left.\begin{array}{ll}\text{Diffusion} & : \\ \text{Focus noise} & : \end{array}\right\}$$ 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

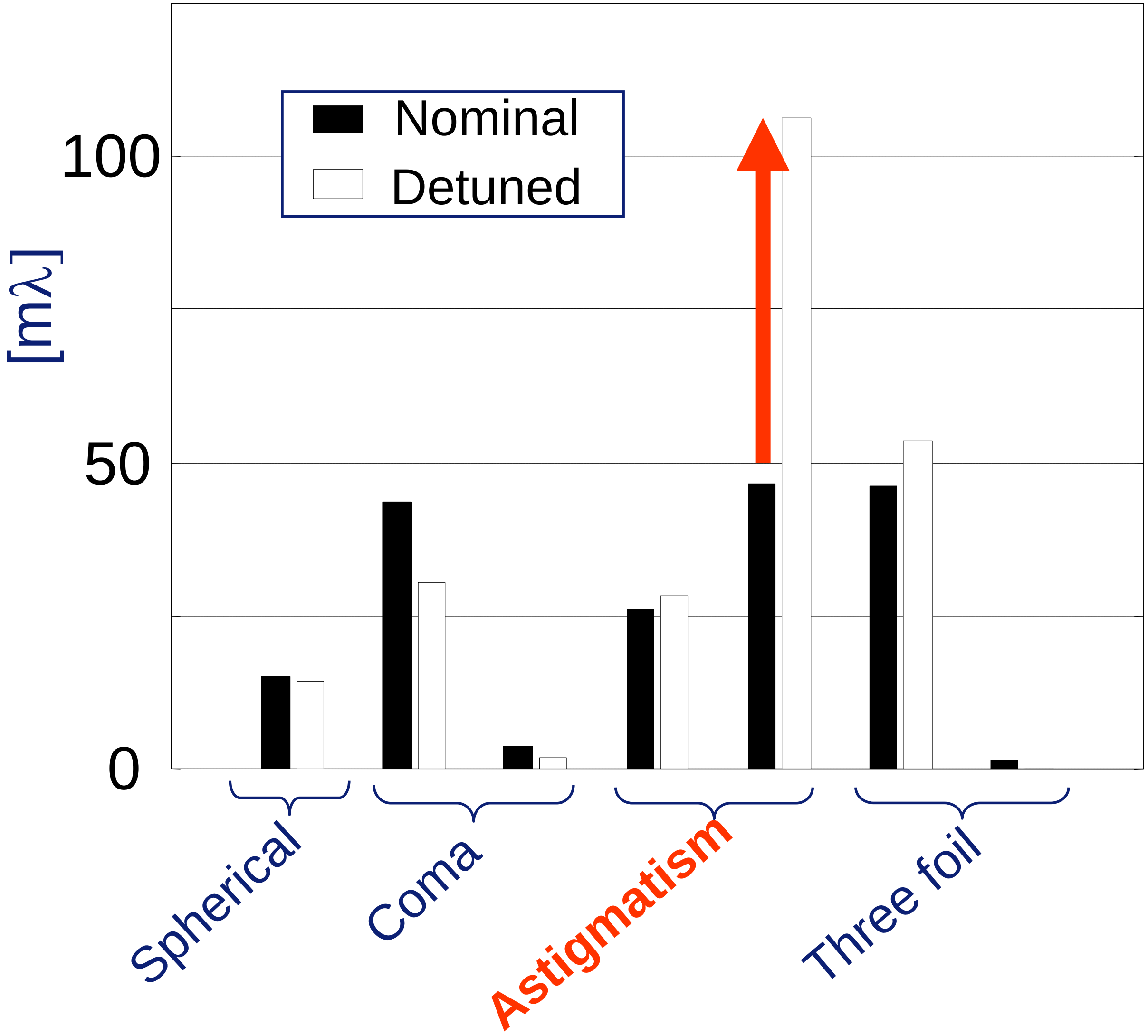
Spherical = 34 mλ

Diffusion = 31 nm

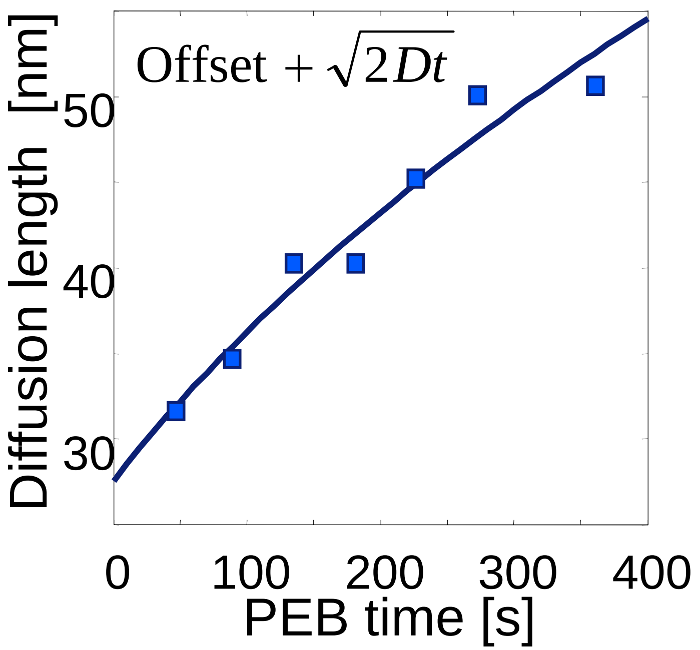
Focus noise = 195 nm

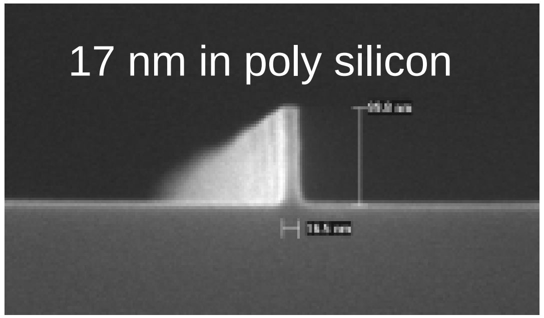
RMS fit error 1.5 % typical

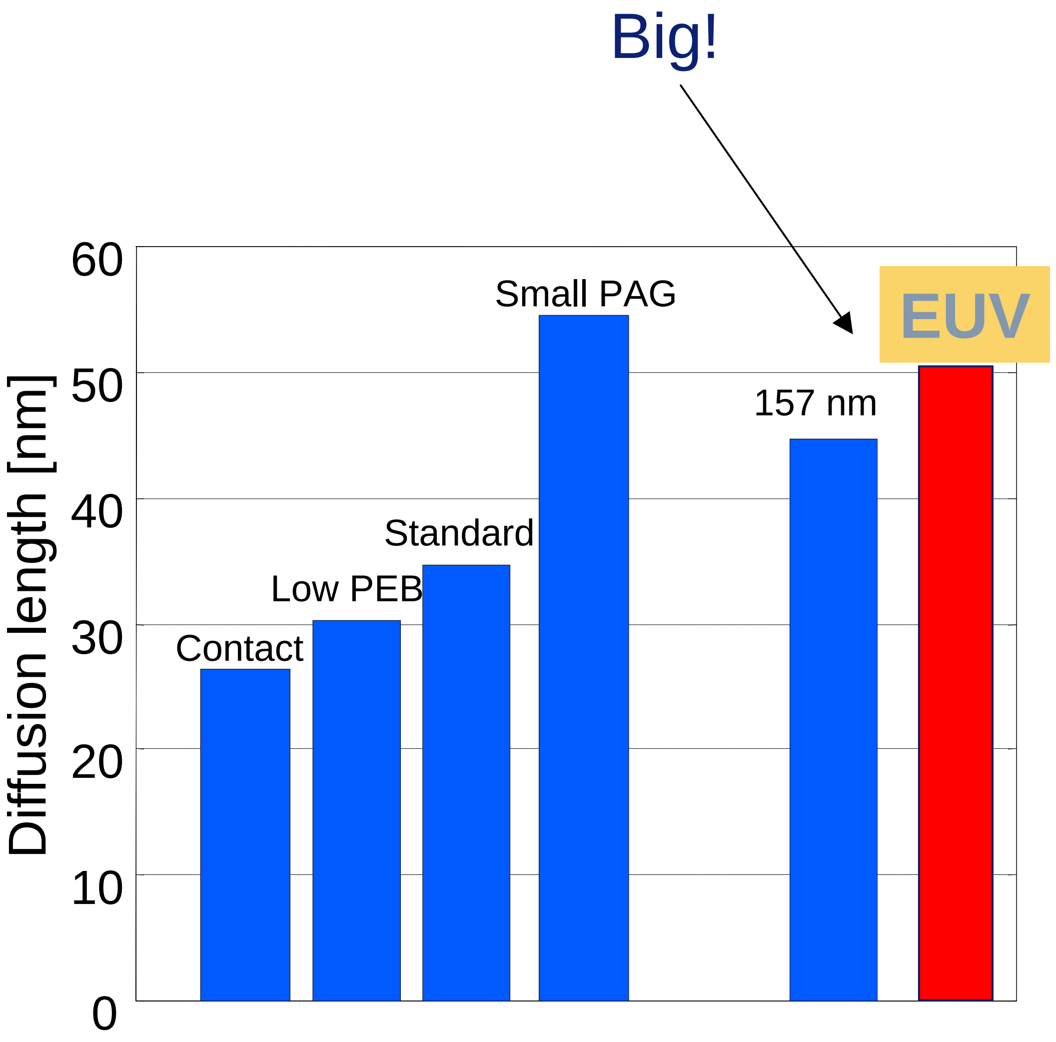
Aberrations



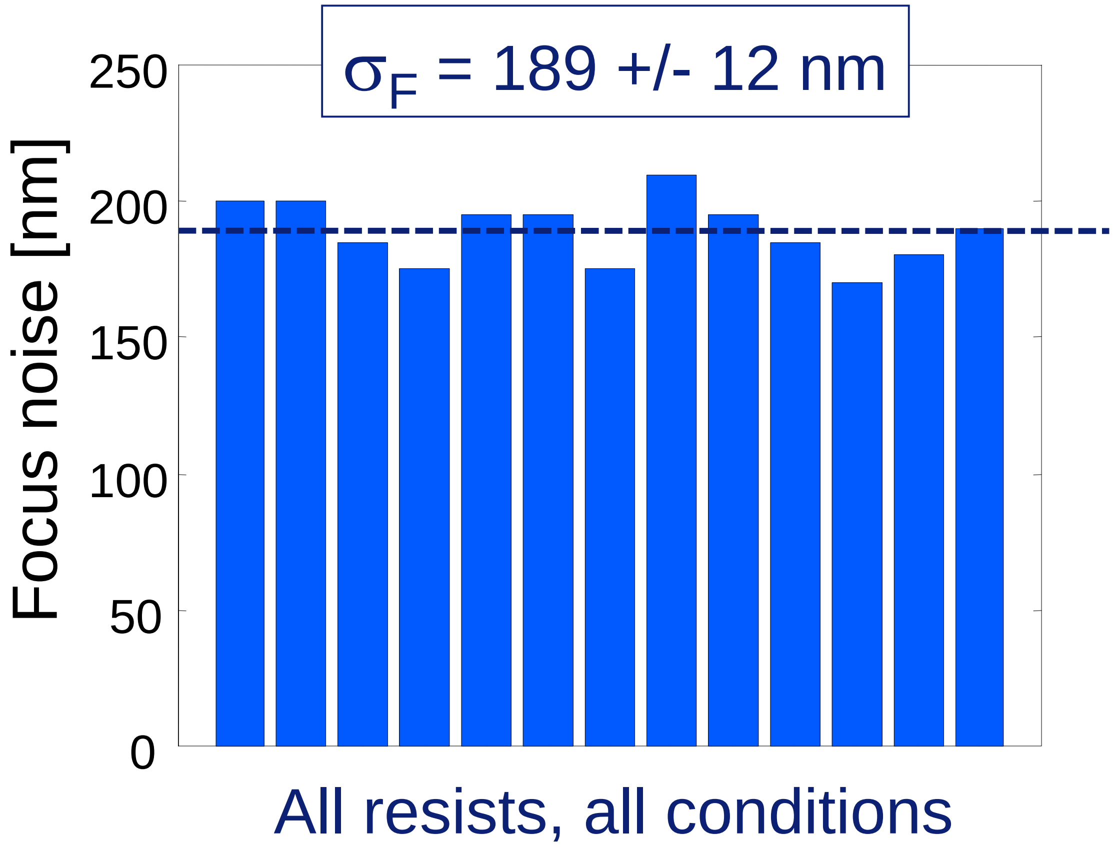
Diffusion




17 nm in poly silicon



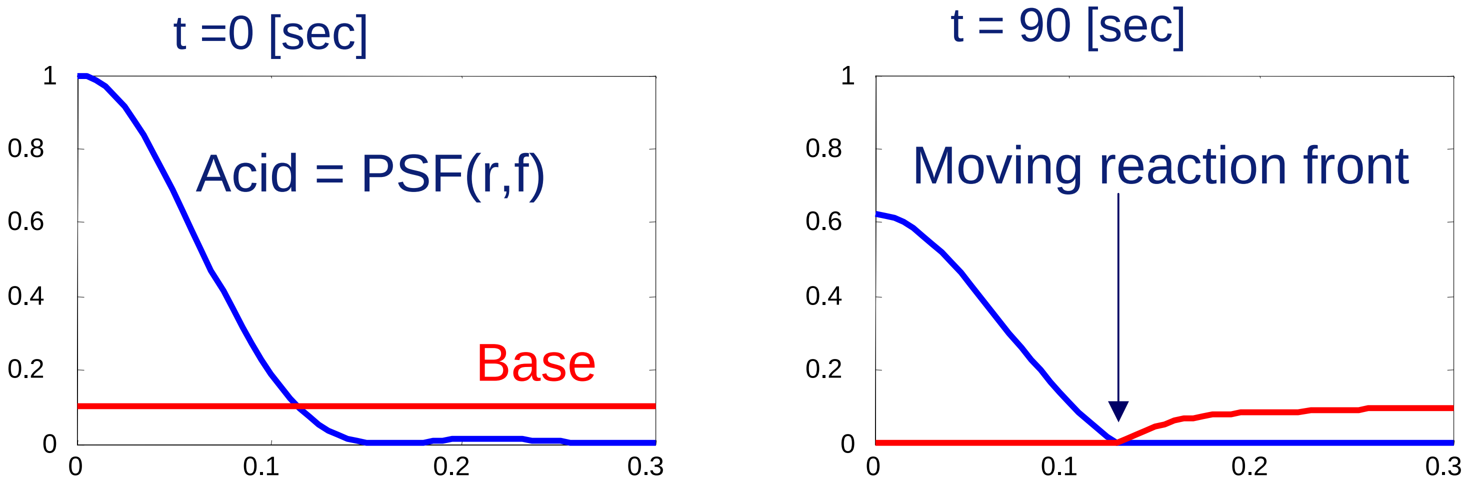
Chromatic aberrations



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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