Experimental Determination of Lens Aberrations from the Intensity Point-Spread Function in the Focal Region

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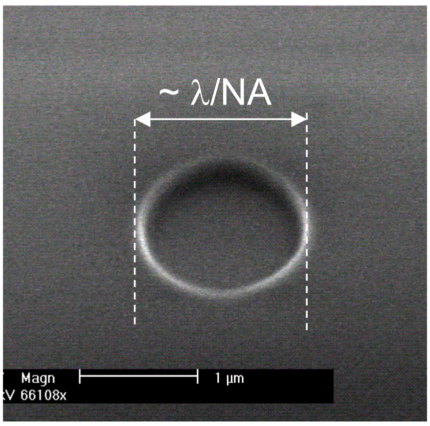
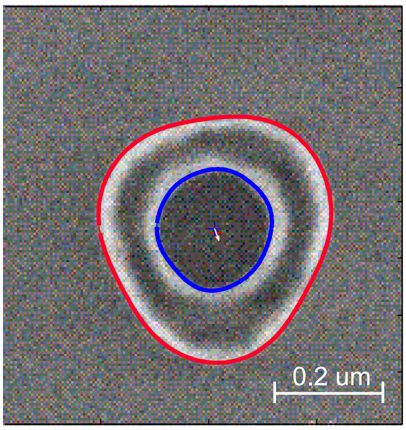
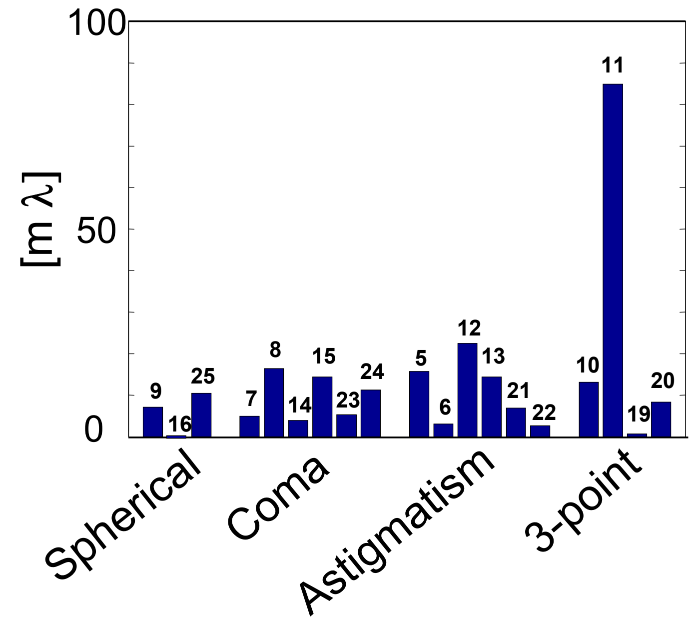
The old aberration ring test

Phase dot on the reticleprints a resist donut





You get the Zernikes, but ...

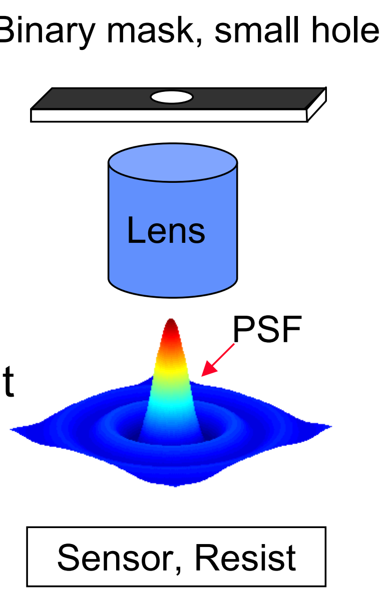


- Phase shifting mask
- NA,σ , feature size
- Simulator for calibration

- A simple alternative?

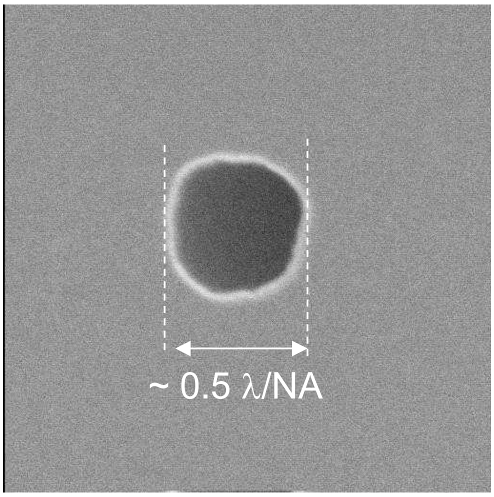
The Point-Spread Function is an alternative

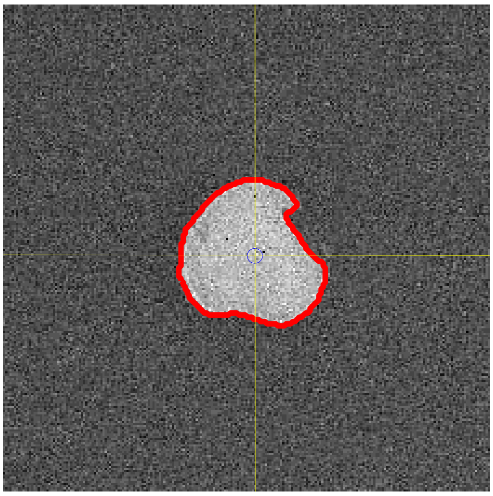
- The PSF is the image of a small hole
- Simple binary mask
- Characteristic for the lens
- Illumination and wavelength independent



The point-spread function approach

Hole in binary reticle prints a single contour PSF





How do you get Zernikes out of contours ?

First we need a mathematical description of PSF

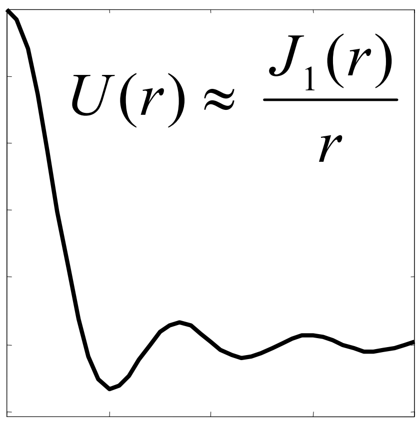
Outline

- Introduction
- Forward calculation: from aberrations to PSF
- Backward calculation: from observed PSF to aberrations
- Experiments: validation

Point-spread function: historical overview

- Airy (1835) : best focus
- Rayleigh (1879) : resolution
- Lommel (1885) : out of focus

No aberrations



“Nijboer-Zernike theory of aberrations” (1942)

E-Field = Airy + Zernike • aberrations

$$U(r) \approx 2\frac{J_1(r)}{r} + 2\sum_{n,m} i^{n+1}\alpha_{nm}\frac{J_{n+1}(r)}{r}\cos m\theta$$

- Best focus, small aberrations
- Defocus included for a few low order terms only

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Extended Nijboer-Zernike theory (2001)

Augustus Janssen

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

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

- Through-focus, symmetry, orthogonality, convergence
- Aberrations of all orders allowed
- Old theory (Airy, Lommel, Nijboer) special case of new theory

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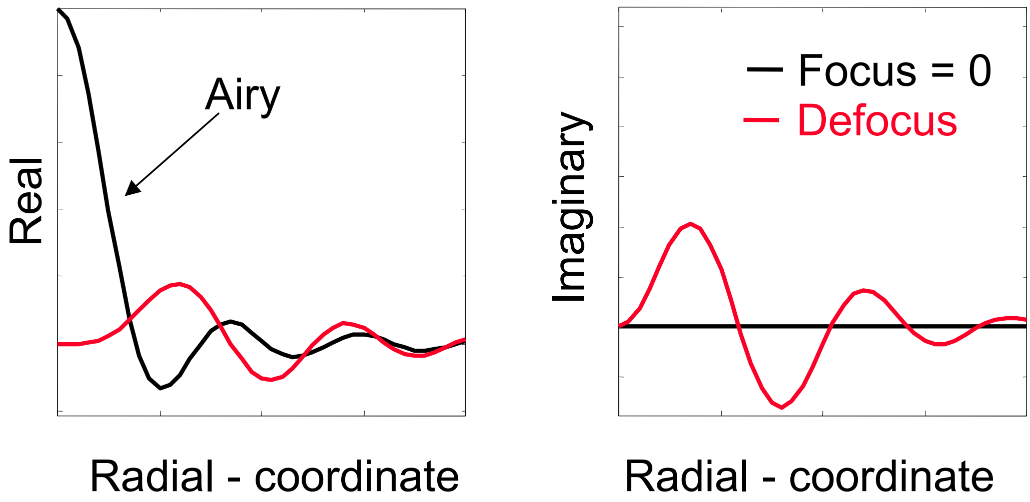
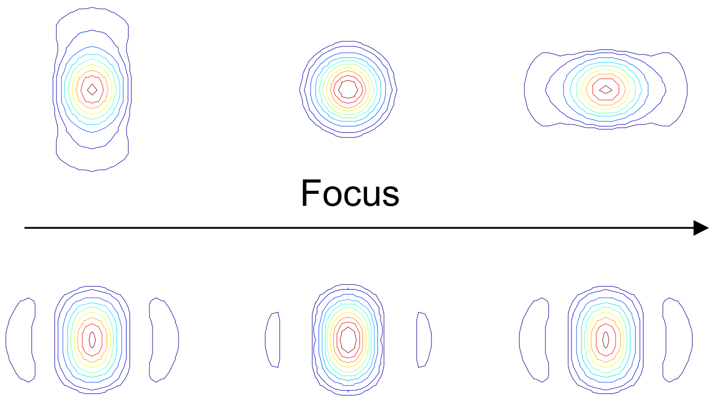
Example : through - focus Airy pattern $V_{00}(r,f)$



Generalization ENZ theory

- Phase



- Transmission
- Extension to finite hole size, large aberrations

Outline

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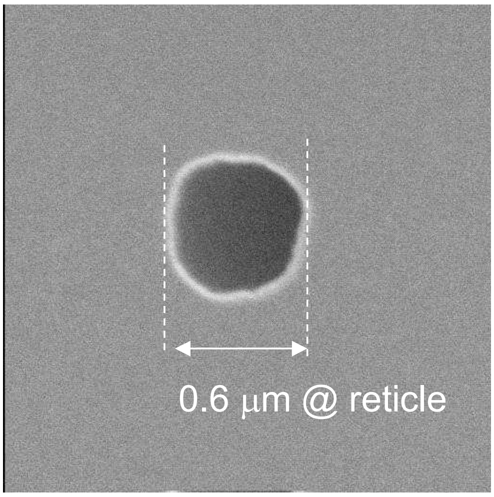
Recipe for phase retrieval

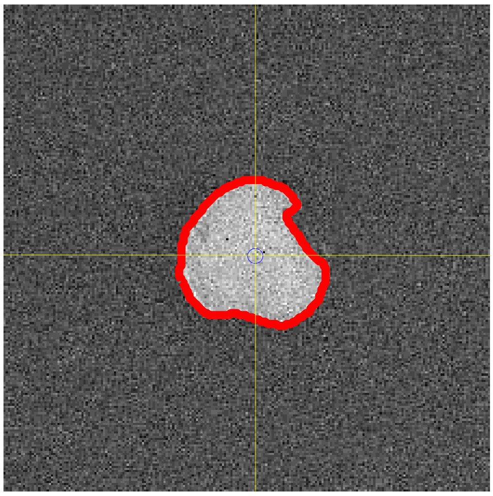
$$\text{Observed intensity} = \sum \alpha_{nm} \text{ Basic functions } (V_{00} V_{nm})$$

- Match experiment to theory
- The Zernike coefficients are found on solving a linear system of equations, see paper for details.

Applications to a wafer scanner

Hole in binary reticle prints a single contour PSF





Finite hole size is accounted for.

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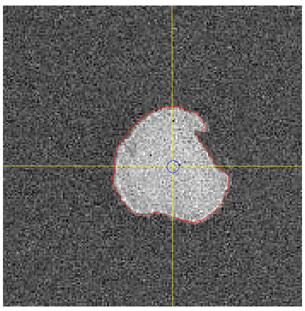
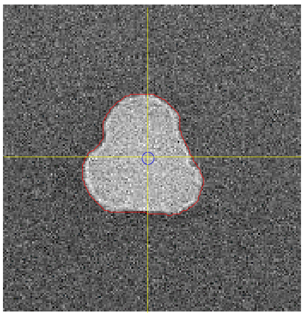
Different tools, same mask

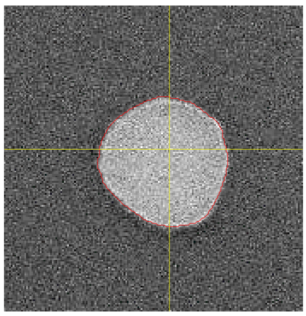
λ = 193, NA = 0.45



λ = 193, NA = 0.63



λ = 248, NA = 0.70



1 μm

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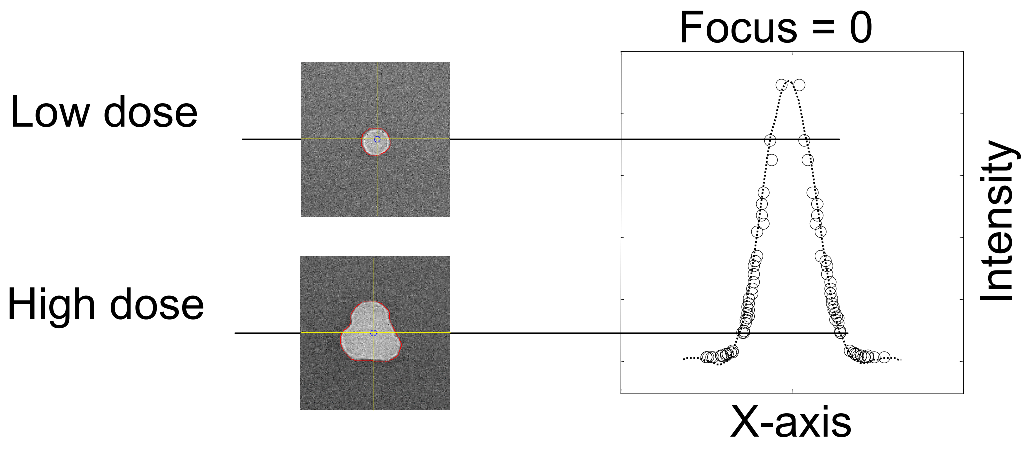
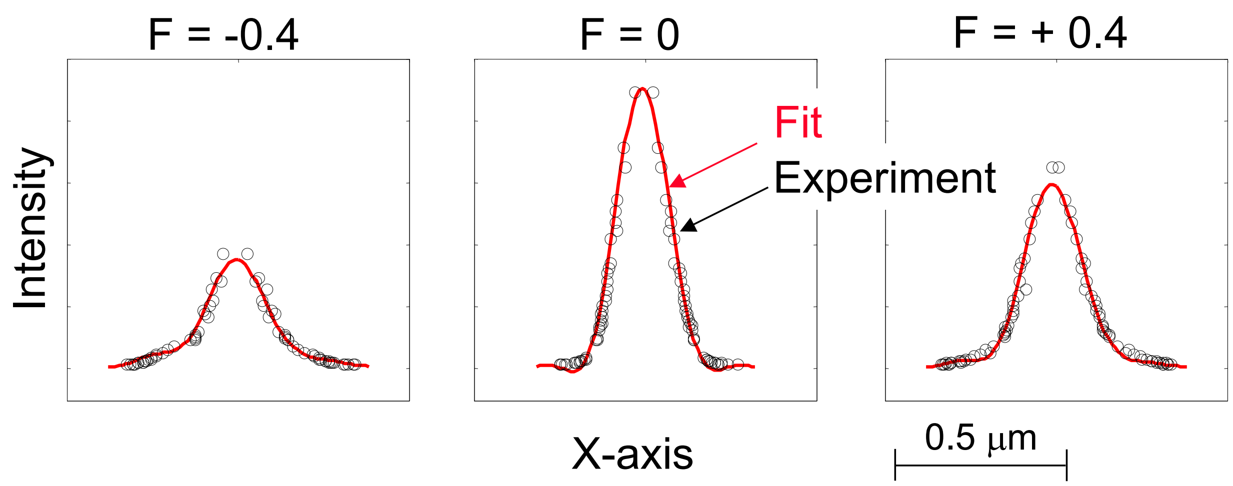
Contours to Intensity



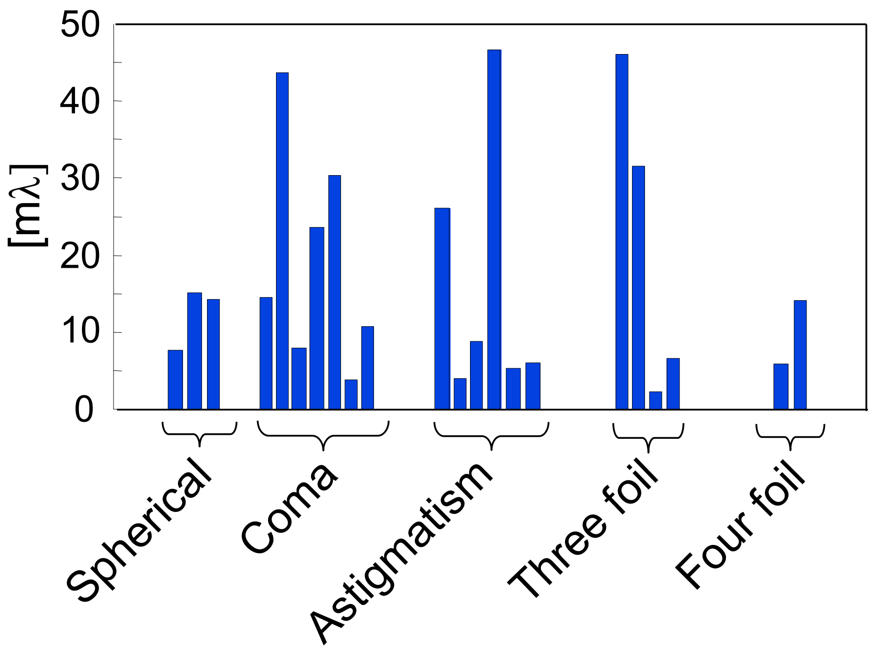
FEM: combine contours into a through focus PSF

Intensity to Zernikes



- Data fit uses retrieved Zernikes, goodness of fit typical σ ~ 2 %

You get the Zernikes.



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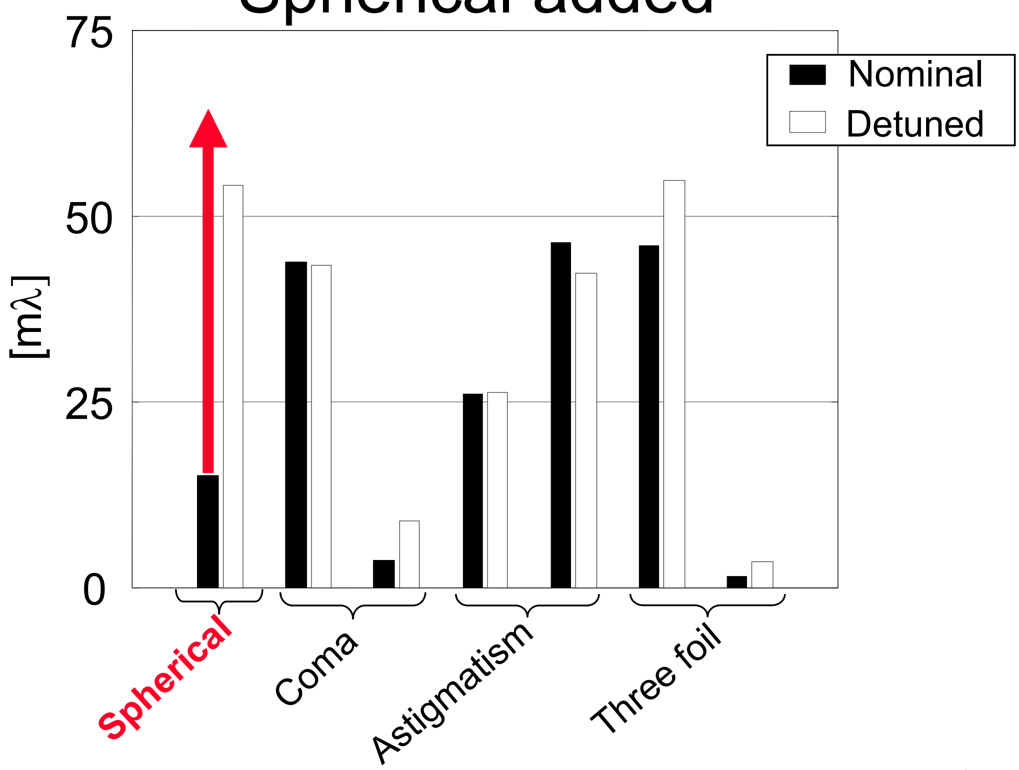
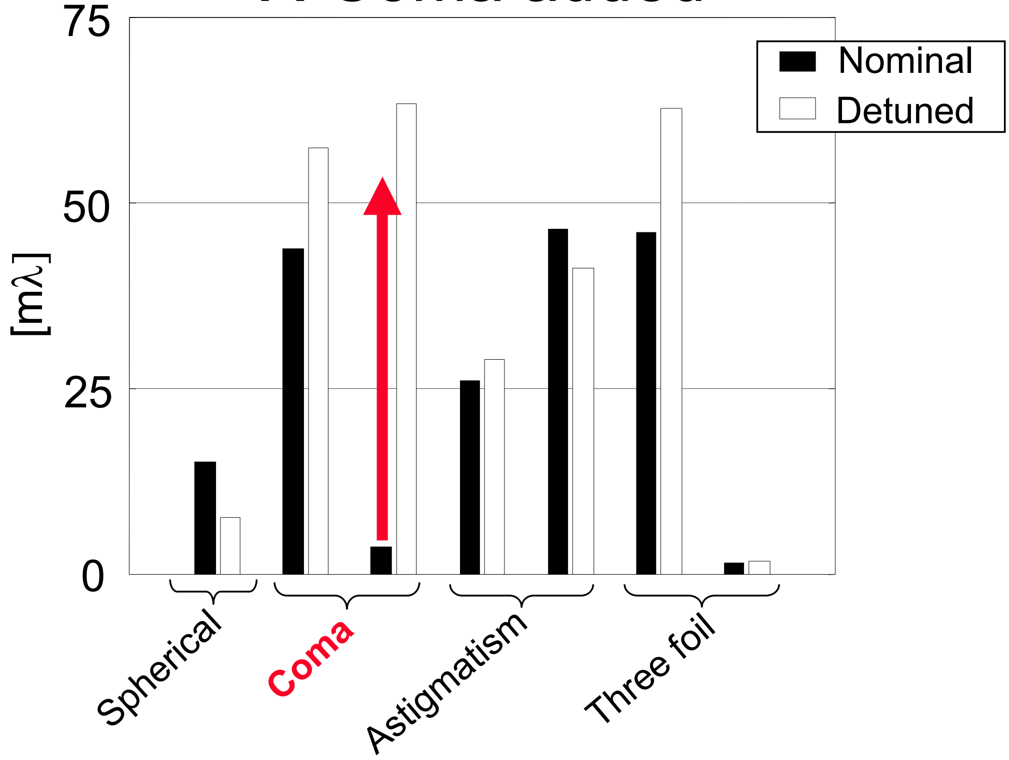
Detuningexperiment

- Validate parameters by detuning experiment
- Keyboard commanded offset movable lens elements
- Compare nominal to detuned state of exposure tool

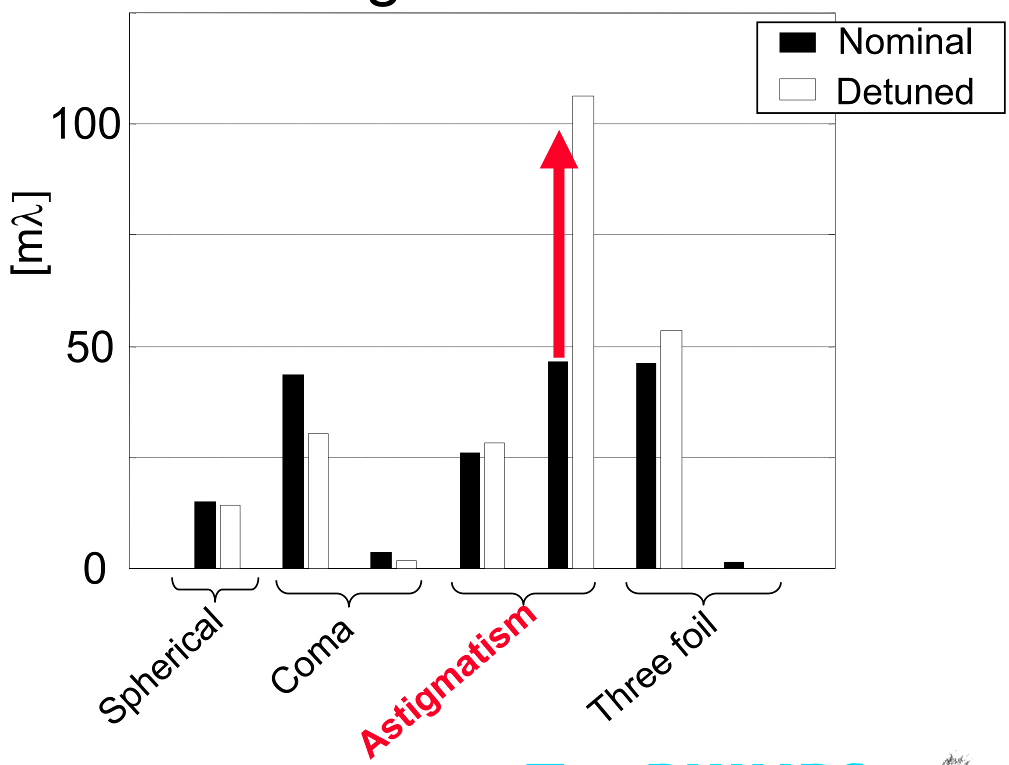
Spherical added



X-Coma added



HV-astigmatism added



Summary

- Simple experimental method to characterize a lens
- Observe the PSF; use the ENZ-theory
- Advantages:
    - Binary mask, multiple tools
    - Single NA, feature size
    - σ-independent
    - Results in $m\lambda$

Acknowledgement

The authors wish to thank Hans Kwinten, David Van Steenwinckel, Michael Benndorf and Johannes Wingerden from Philips Reseach Leuven and Peter de Bisschop from IMEC for their valuable input and experimental support.

Recipe for phase retrieval

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

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

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

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

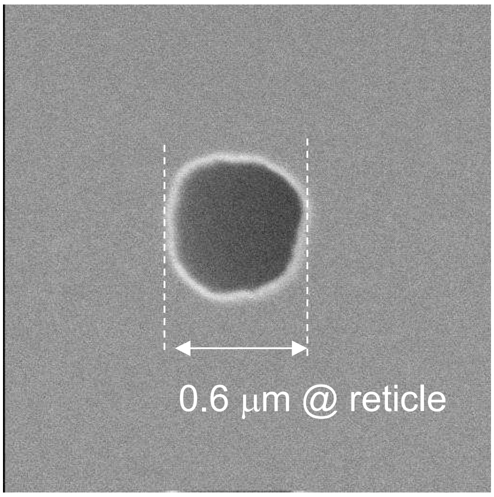
Take inner products :

$$(\psi^m, \psi_{n'}^m) = \sum_{\mathrm{n}} \alpha_{\mathrm{nm}} (\psi_n^m, \psi_{n'}^m)$$

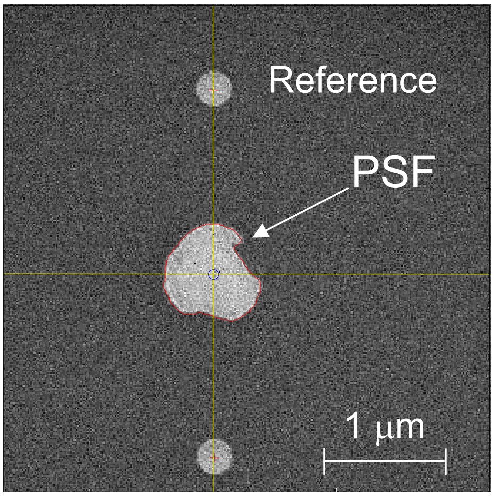
- The Zernike coefficients are found on solving a linear system of equations.

Applications to a wafer scanner

Reticle

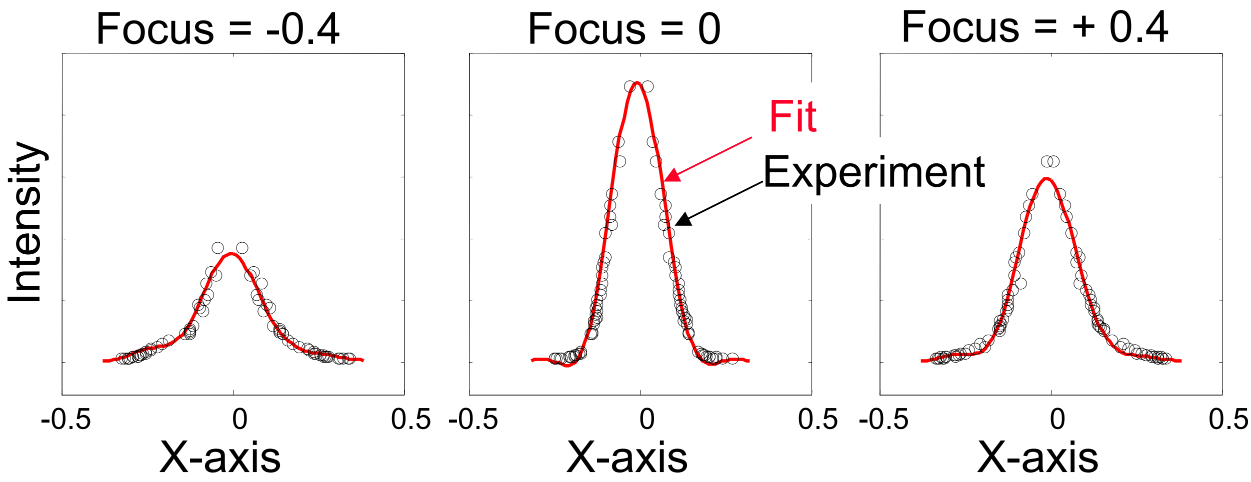


Wafer



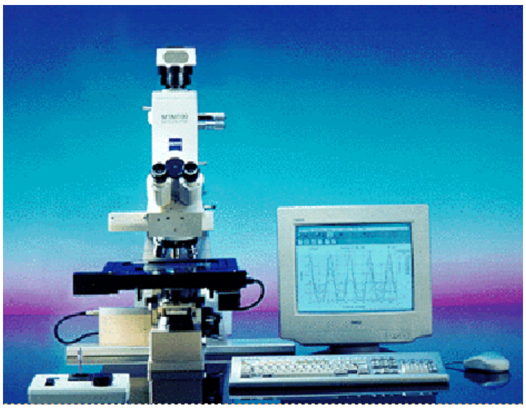
One exposure: single contour point-spread function

Intensity to Zernikes



- Data fit uses retrieved Zernikes, goodness of fit typical σ ~ 2 %

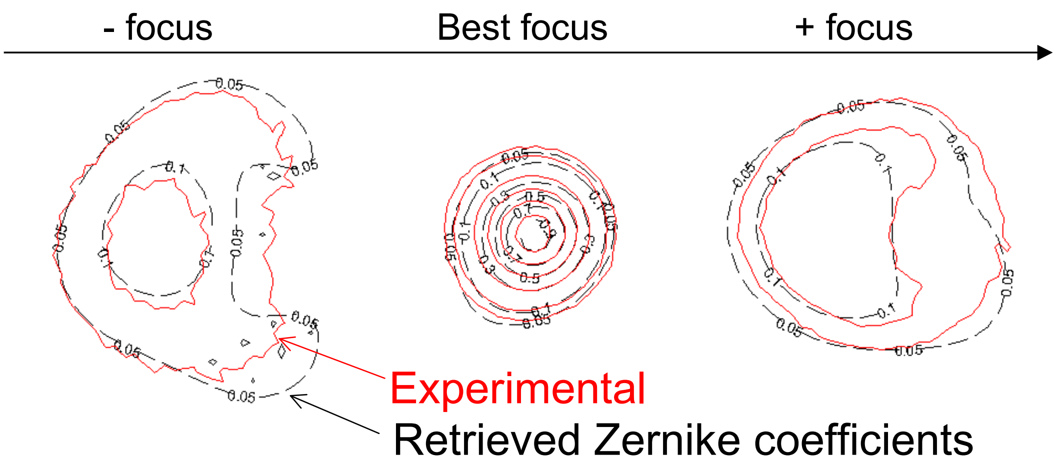
Aerial image measurement system



- 193 nm Microscope + CCD camera
- Matching simulation to experiment, mimics a stepper (*Na*,σ)
- Reticle inspection (defects)

Through-focus aerial image of an isolated hole

(λ=193 nm MSM-100)



The dominant term is high order coma