New Directions For Optical Critical Dimension Metrology

18 APRIL 2024

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Motivation and Approach

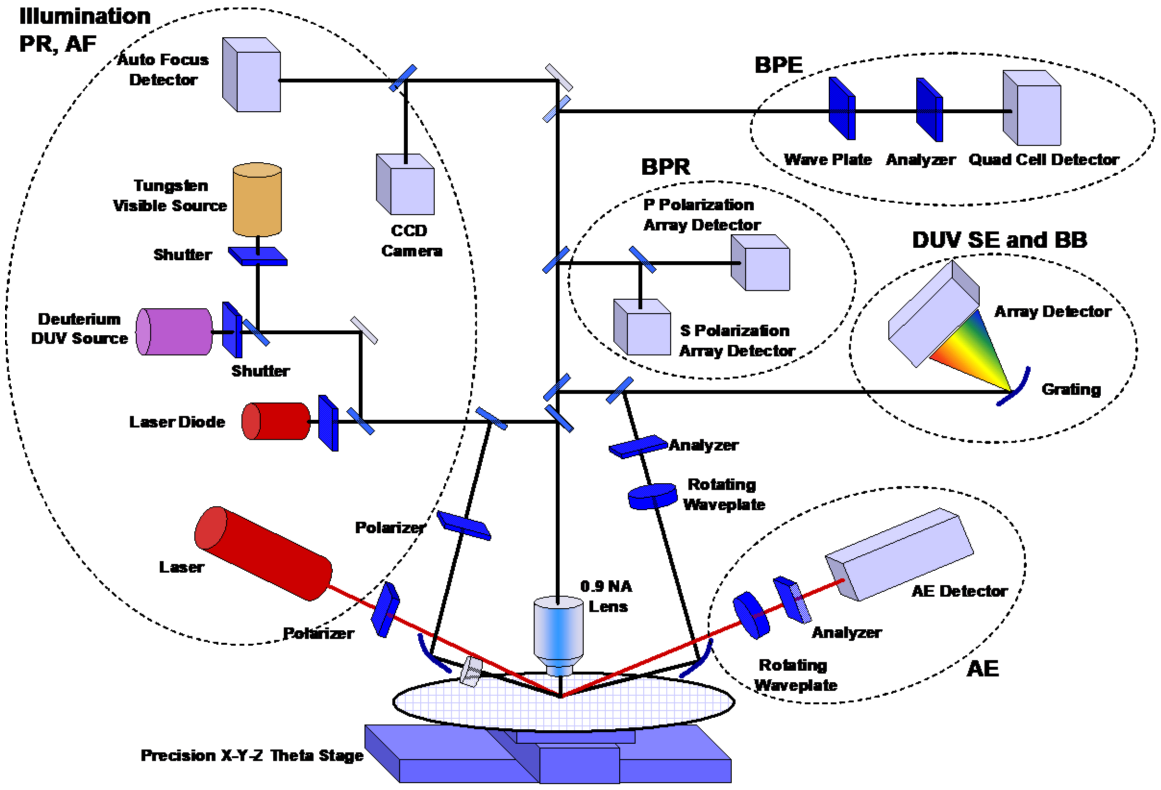
Address the limitations of existing OCD technologies

- Break parameter correlations by massive increase in number of incident angles measured.
  - Correlations occur when signal response to 2+ parameters are effectively the same.
  - When correlations occur, measurement capability is reduced.
- Reduce probe size
  - Some array sizes are below 10µm.
  - Probe within array variation, especially close to the edge of arrays.

Approach

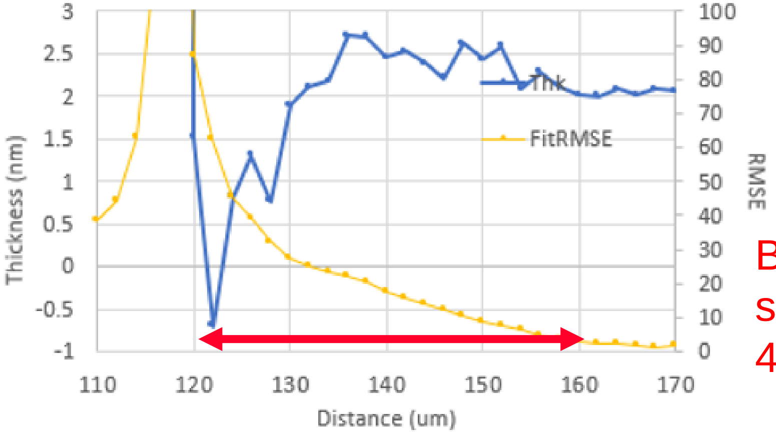
- Instrument based on microscopy with small field size: probe size limited by diffraction to ≈ 1µm or larger.

Non-interferometric Methods



"One can optimize reflection or transmission as a function of angle at a single wavelength or wavelength at a single angle, but not both simultaneously without degrading both" – Jon Opsal

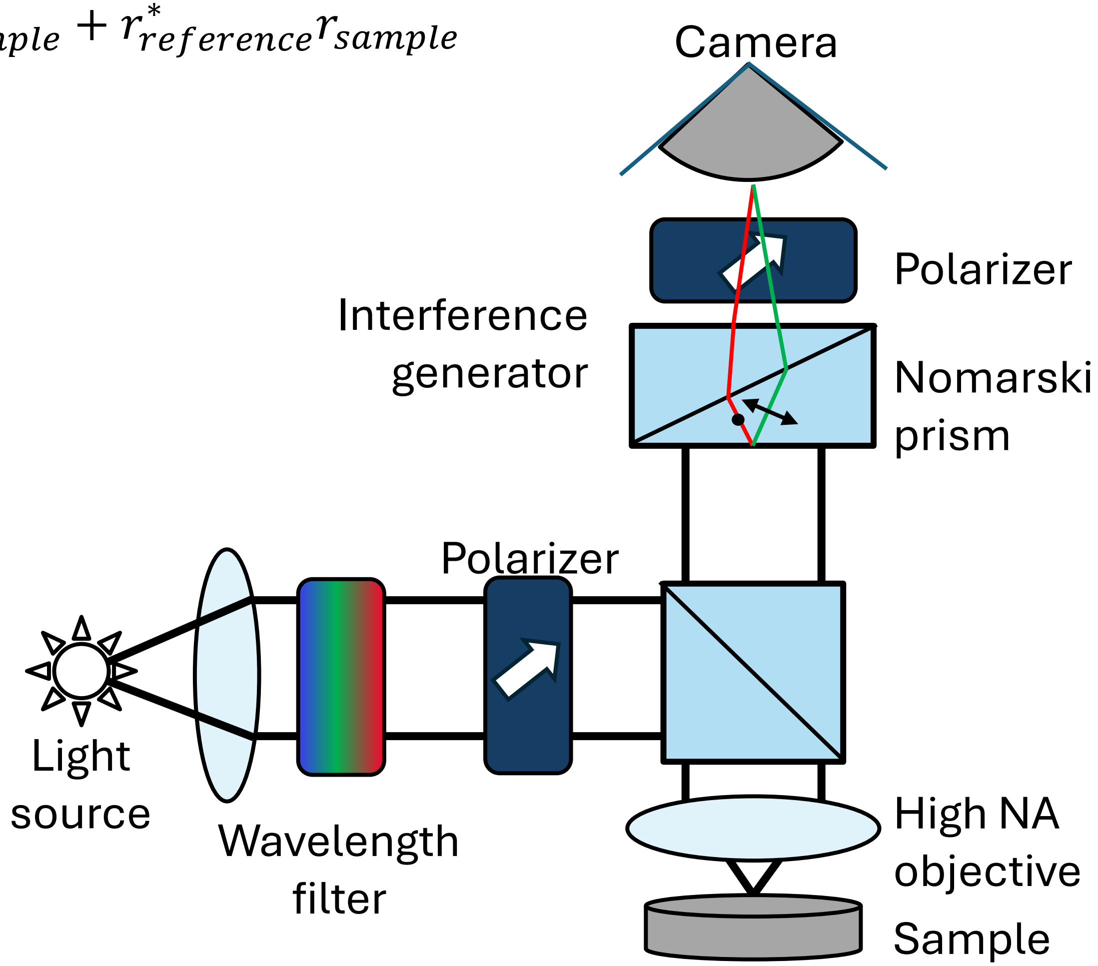
- BPR – Beam Profile Reflectometry (673 nm)
  - Pupil plane: multiple angles, one wavelength, one intensity.
- BPE – Beam Profile Ellipsometry (673 nm)
  - Pupil plane: multiple angles, one wavelength, full Mueller Matrix.
- AE – Absolute Ellipsometry (633nm)
- Vis – Visible Spectrometry (470-870 nm)
- BB – BroadBand Spectrometry (190-840 nm)
- RCSE – Rotating Compensator Spectroscopic Ellipsometry (190-840)
  - One angle, spectroscopic, full Mueller Matrix.



BPE signal is sensitive to edges 40µm away

Interferometry

- $\frac{I_{out}}{I_{in}} = \left|r_{reference}\right|^2 + \left|r_{sample}\right|^2 + r_{reference}\, r_{sample}^* + r_{reference}^* r_{sample}$
- Interferometry allows measurement of the complex reflectance of the sample
- Examples: SIPE (J. Jung et al, *Proc. SPIE 11611, Metrology, Inspection, and Process Control for Semiconductor Manufacturing XXXV*, 2021).



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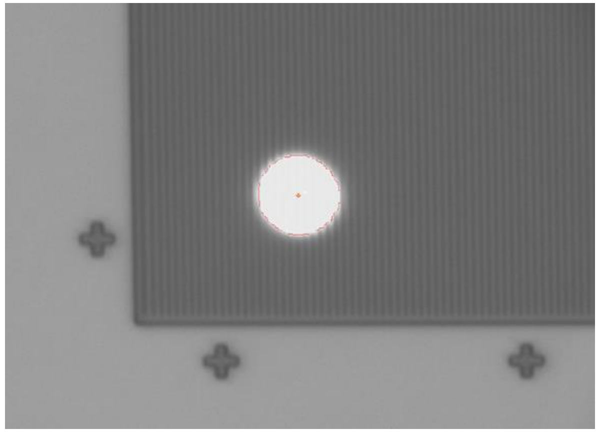
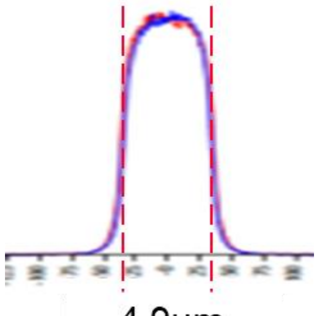
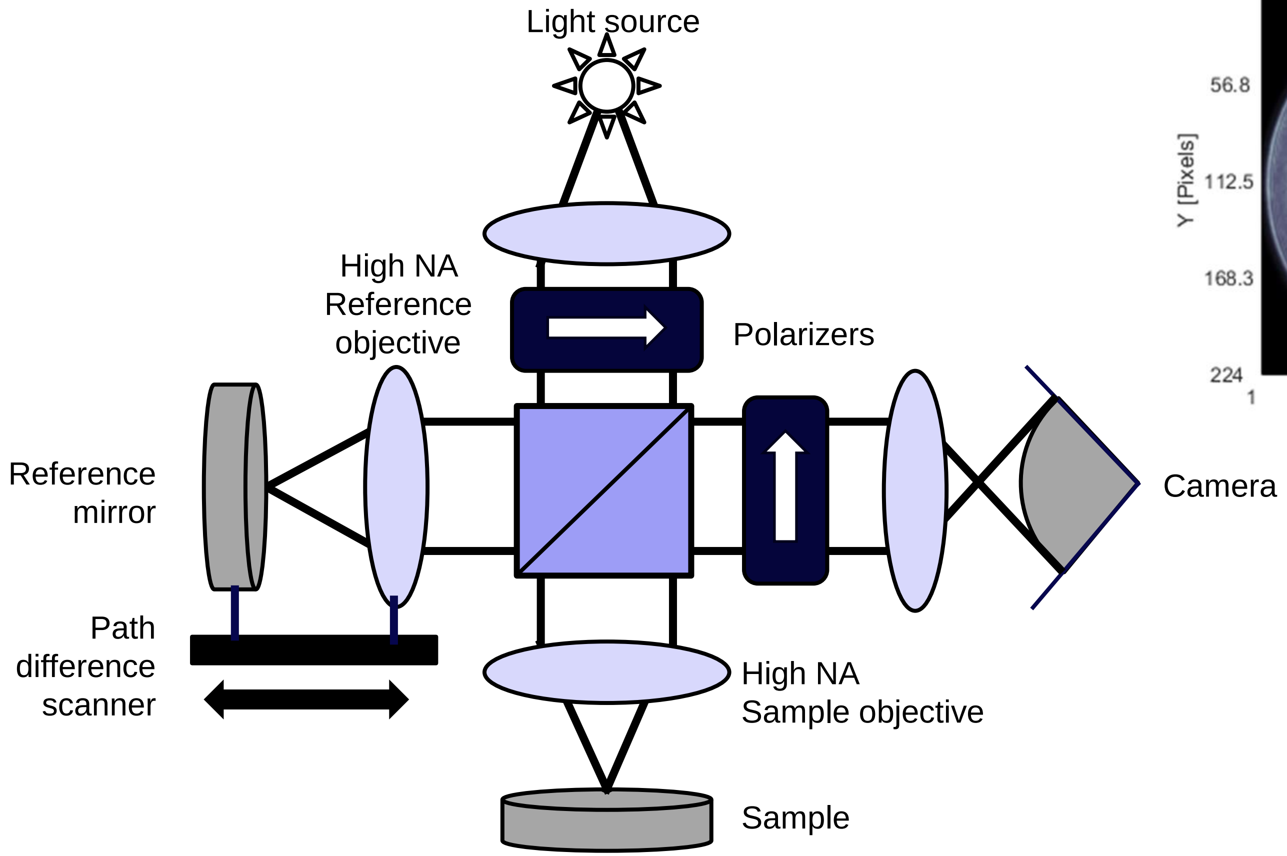
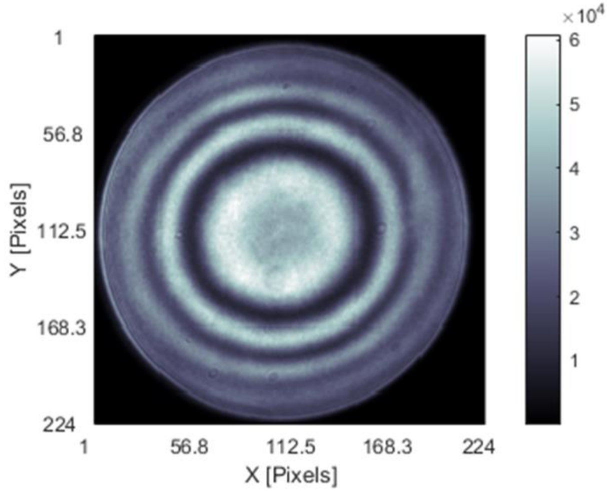
Pupil Plane Interferometry

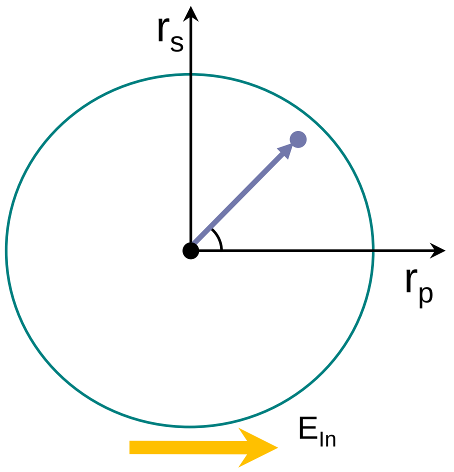




Spot size is controlled by field stop







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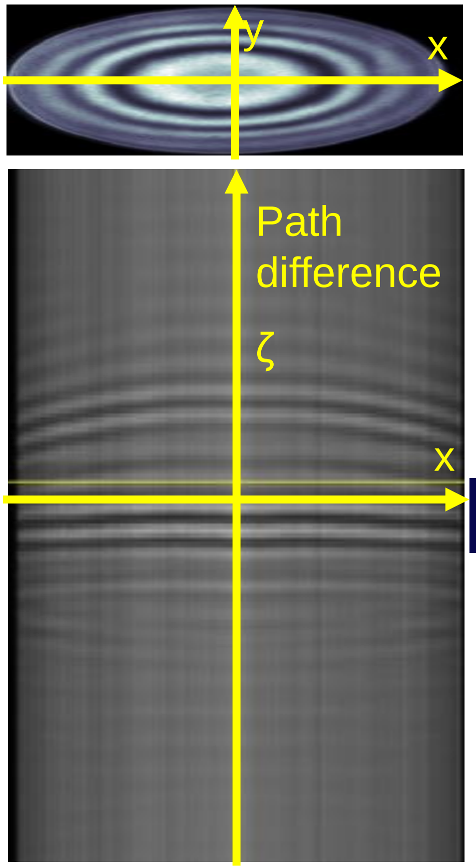
Approach

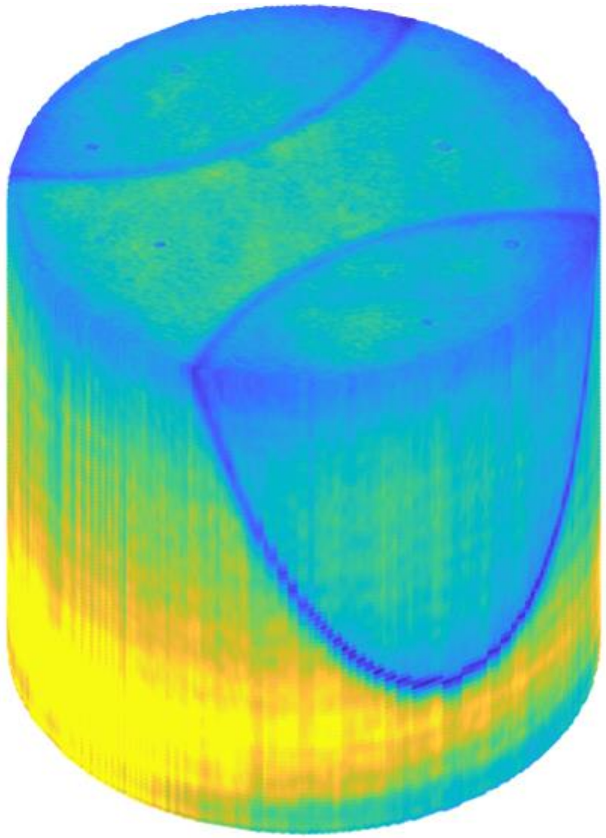
- Instrument based on microscopy with small field size: probe size limited by diffraction to ≈ 1µm or larger.
- Pupil plane detection allows measurement of sample reflection at many incident angles.
  - Unlike in the image plane, each pixel is at a unique angle, simplifying simulation of the signal formation.
- Use interferometry to extract complex reflectance.
- Use standard model fitting approaches to estimate sample parameters from measured data.

Signal Processing



Original data

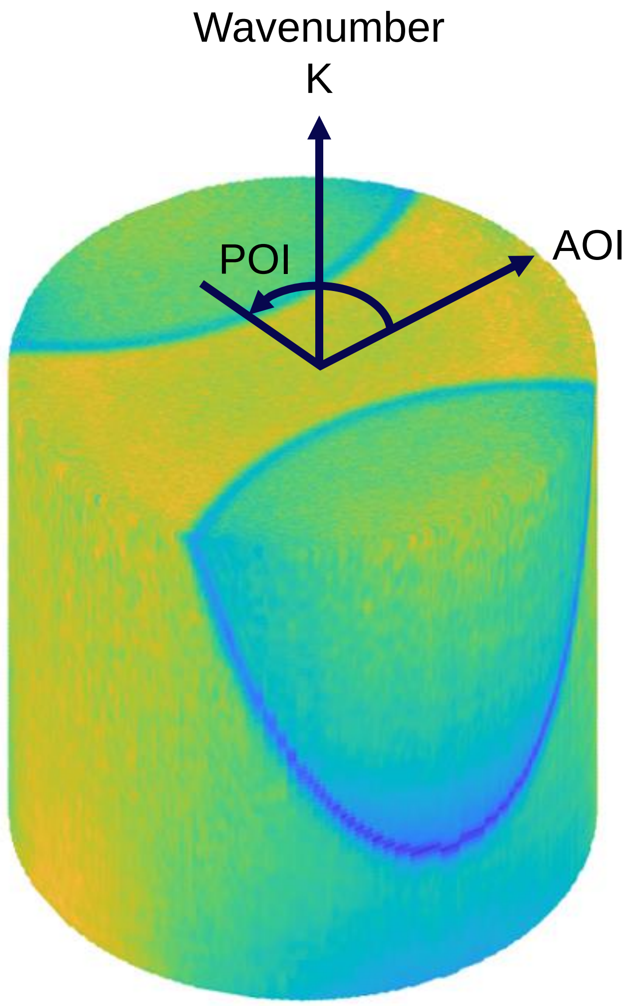
Multiple images as path difference changes



Take FFT at each pixel

$\zeta \rightarrow K$

FFT is **<u>complex</u>**



Remove pupil intensity variation and source spectrum

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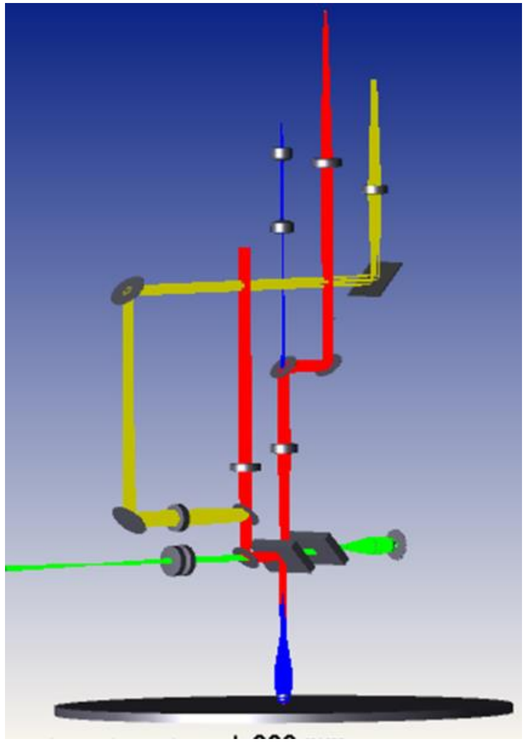
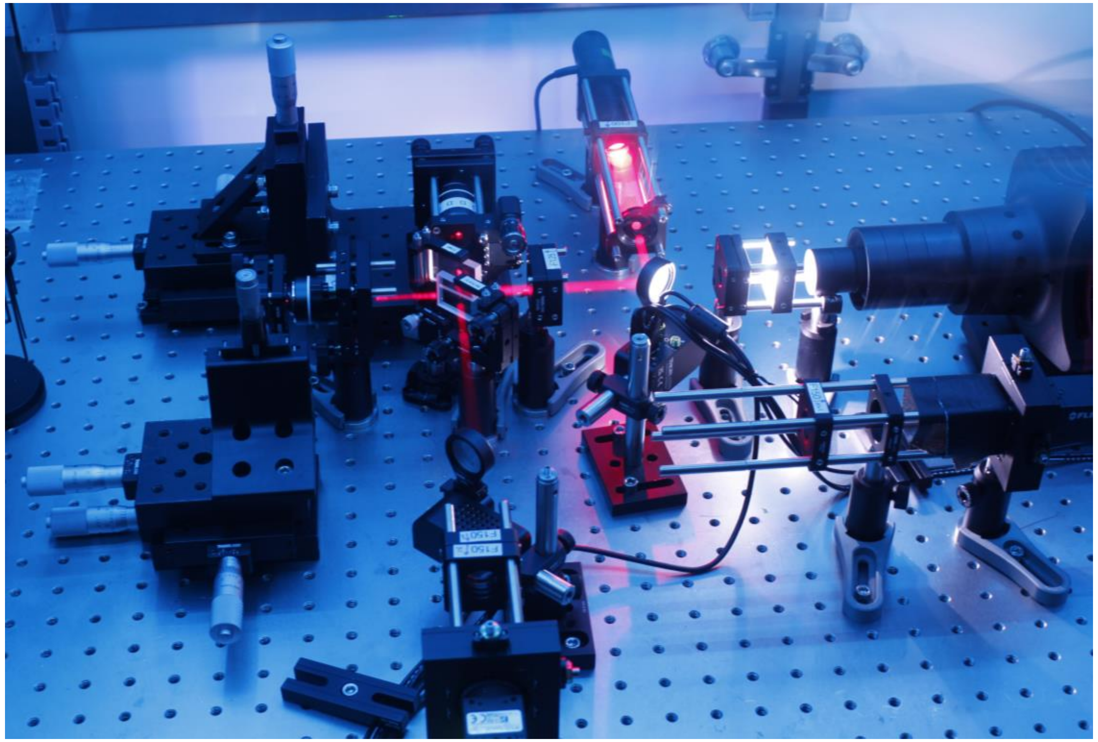
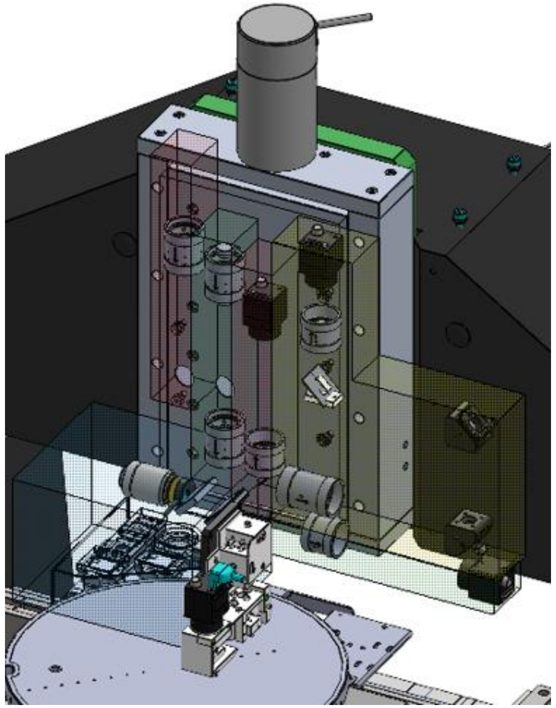
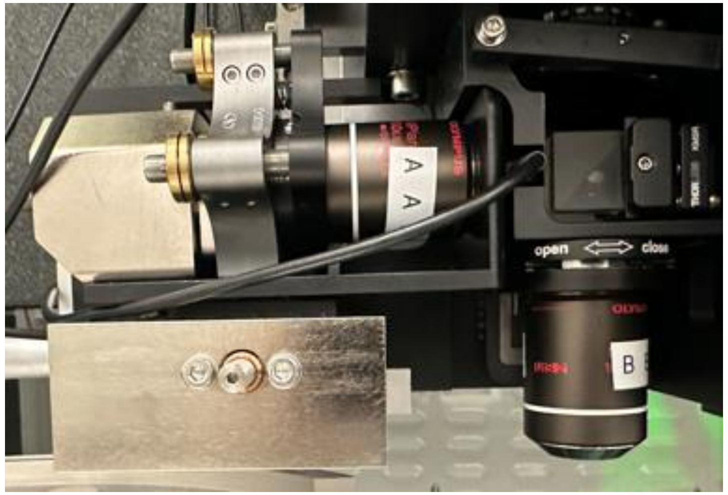
Instrument Realization

Adjustment vs. Stability

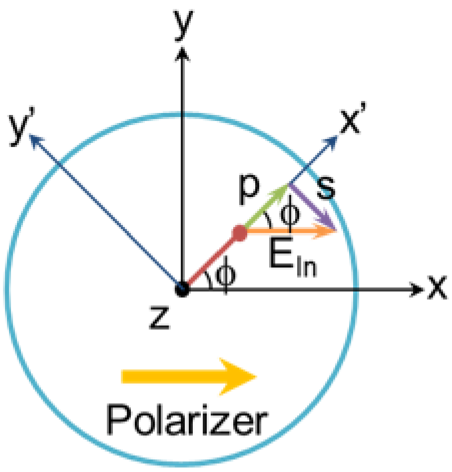


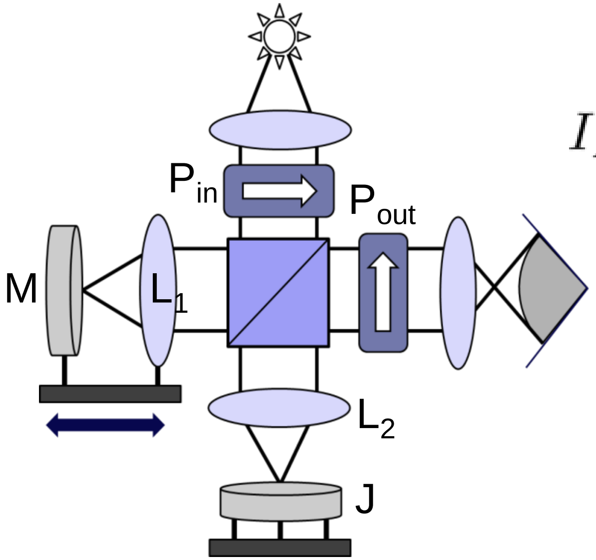






Simplified Analytical Model





$$\mathbf{E}_{out} = \mathbf{P}_{out}\mathbf{B}(\mathbf{L_2RJRL_2} + \mathbf{TL_1ML_1T})\mathbf{BP}_{in}\mathbf{E}_{in}$$

$$\mathbf{E}_{out} = \frac{1}{2}\begin{bmatrix}1 & 0\\ 0 & 0\end{bmatrix}\left(\begin{bmatrix}\mathrm{c}^2 J_{pp} + \mathrm{cs}J_{sp} - \mathrm{cs}J_{ps} - \mathrm{s}^2 J_{ss} & -\mathrm{cs}J_{pp} + \mathrm{c}^2 J_{sp} + \mathrm{s}^2 J_{ps} - \mathrm{cs}J_{ss}\\ \mathrm{cs}J_{pp} + \mathrm{c}^2 J_{sp} + \mathrm{s}^2 J_{ps} + \mathrm{cs}J_{ss} & -\mathrm{s}^2 J_{pp} + \mathrm{cs}J_{sp} - \mathrm{cs}J_{ps} + \mathrm{c}^2 J_{ss}\end{bmatrix}\right.$$

$$\left. + \begin{bmatrix}e^{4\mathbf{i}\pi d/\lambda} & 0\\ 0 & -e^{4\mathbf{i}\pi d/\lambda}\end{bmatrix}\right)\begin{bmatrix}1 & 0\\ 0 & 0\end{bmatrix}\mathbf{E}_{in}$$

$$\begin{aligned} I_{AC} &= \mathbf{E}^*_{out}\mathbf{E}_{out}|_{AC} \\ &= I_0\cos^2(\phi)|J_{pp}|\cos(\Delta_{pp} - 4\pi d/\lambda) \\ &+ I_0\cos(\phi)\sin(\phi)|J_{ps}|\cos(\Delta_{ps} - 4\pi d/\lambda) \\ &- I_0\cos(\phi)\sin(\phi)|J_{sp}|\cos(\Delta_{sp} - 4\pi d/\lambda) \\ &- I_0\sin^2(\phi)|J_{ss}|\cos(\Delta_{ss} - 4\pi d/\lambda) \end{aligned}$$

- I_{AC} is modulation of interferogram.
- Full model:
  - 3D Jones Matrix.
  - Non-ideal system components.
- Use model parameters for sample to determine Jones matrix terms.
- Adjust Jones matrix terms for best fit to experimental signal.

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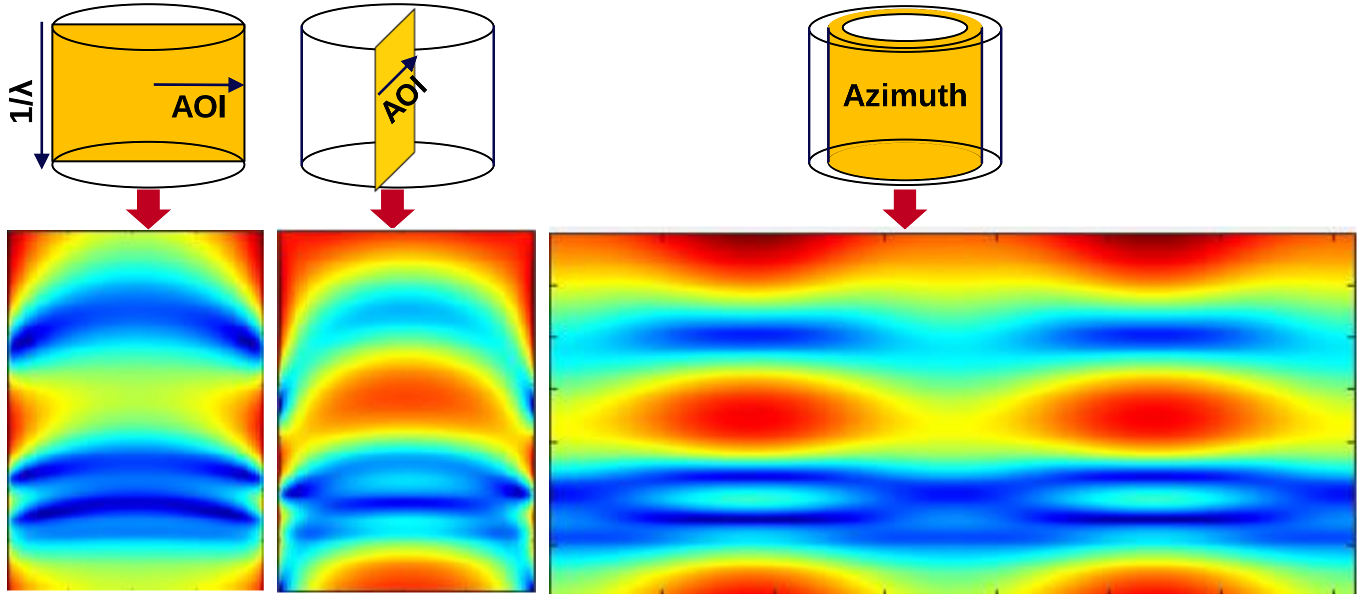
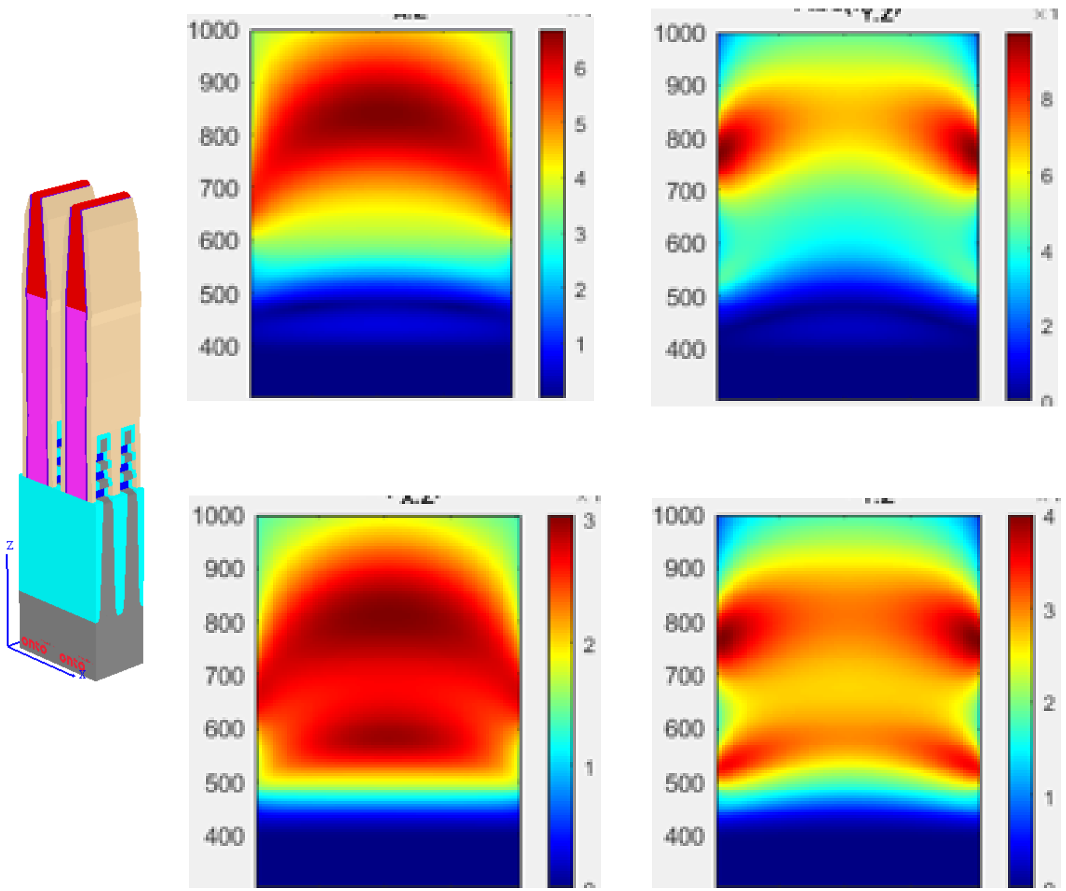
Simulations of Gate-All Around Transistor: CD Sensitivity

Signal intensity projections



Sensitivity to 0.1nm process property change



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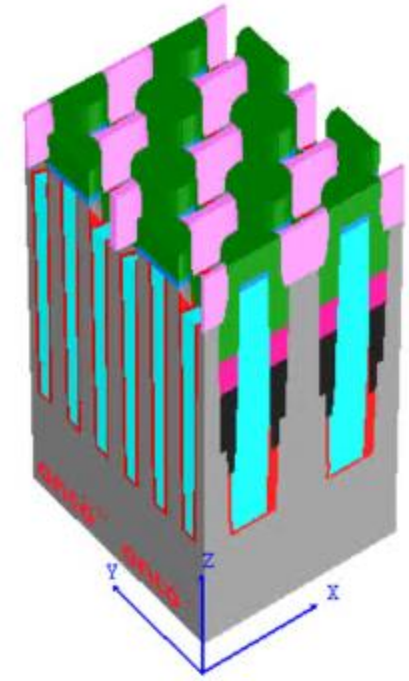
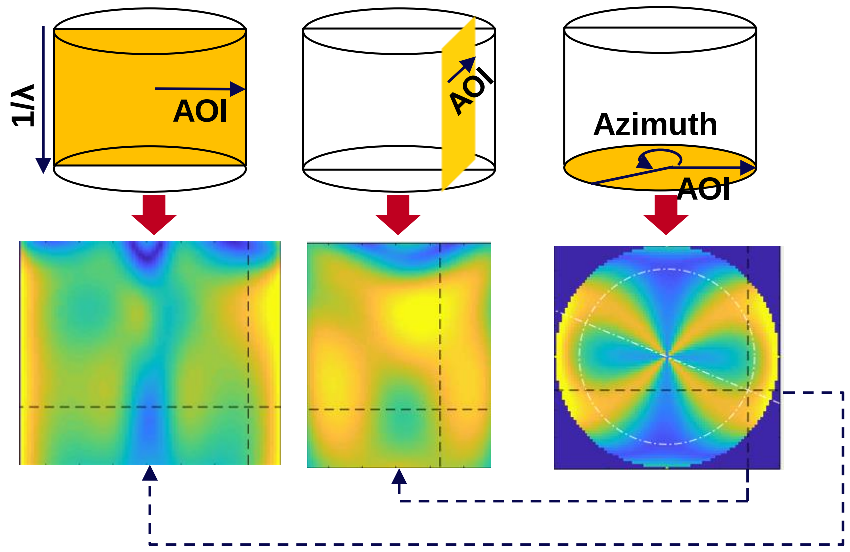
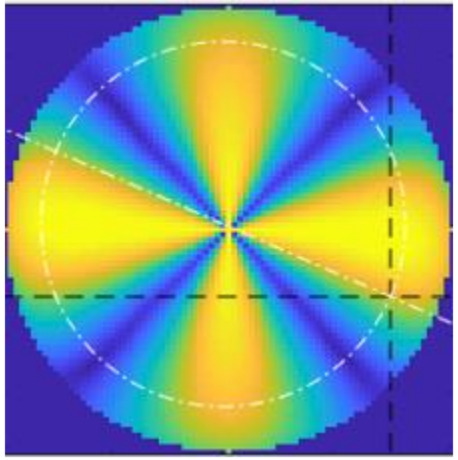
Simulations of DRAM Bit Line Gate Etch: Overlay Sensitivity



Signal intensity projections

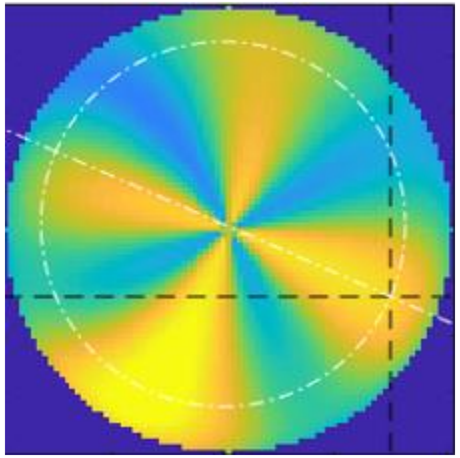


Sensitivity to property change



0.1nm CD change

Pattern symmetry is retained

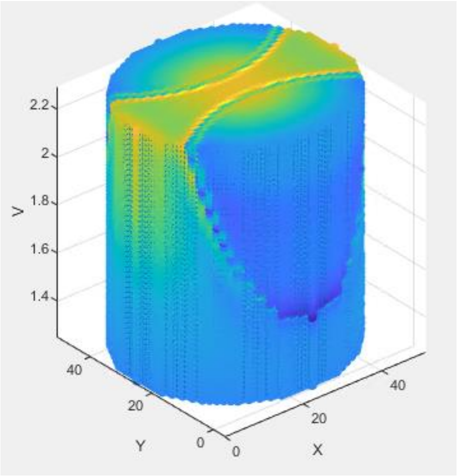


0.1nm overlay

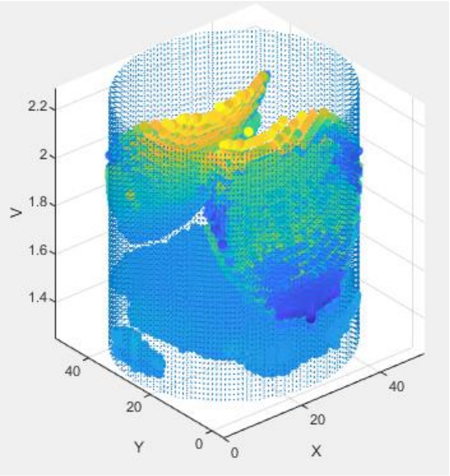
Pattern rotates and becomes asymmetric

Data Selection

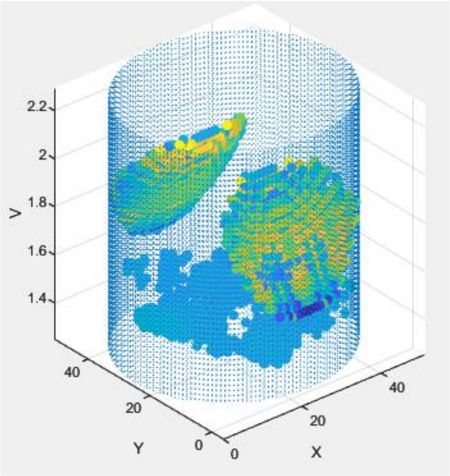
Reduce data volume to a selectable number of the most useful data points



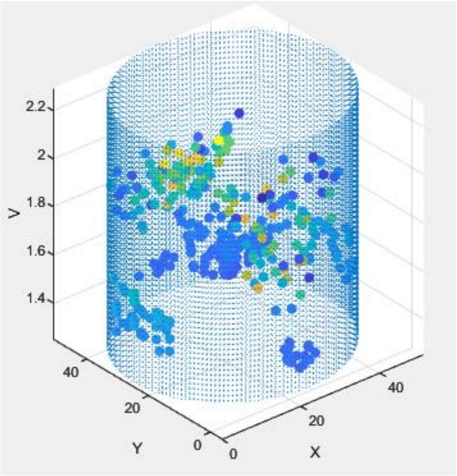
Original data cylinder



Filter 1



Filter 2

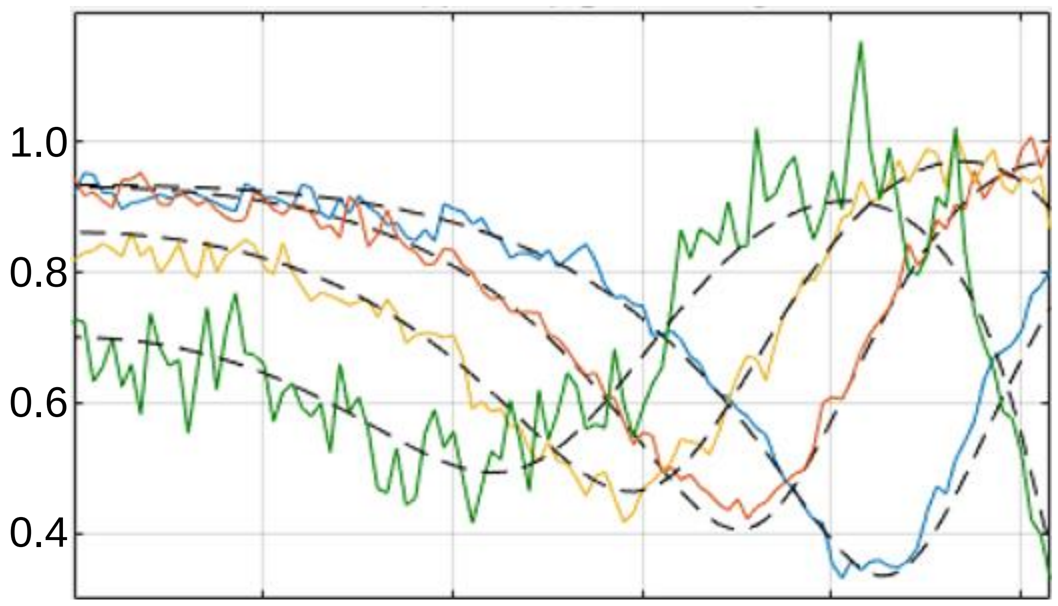


Filter 3

Thin Film Signal and Simulation

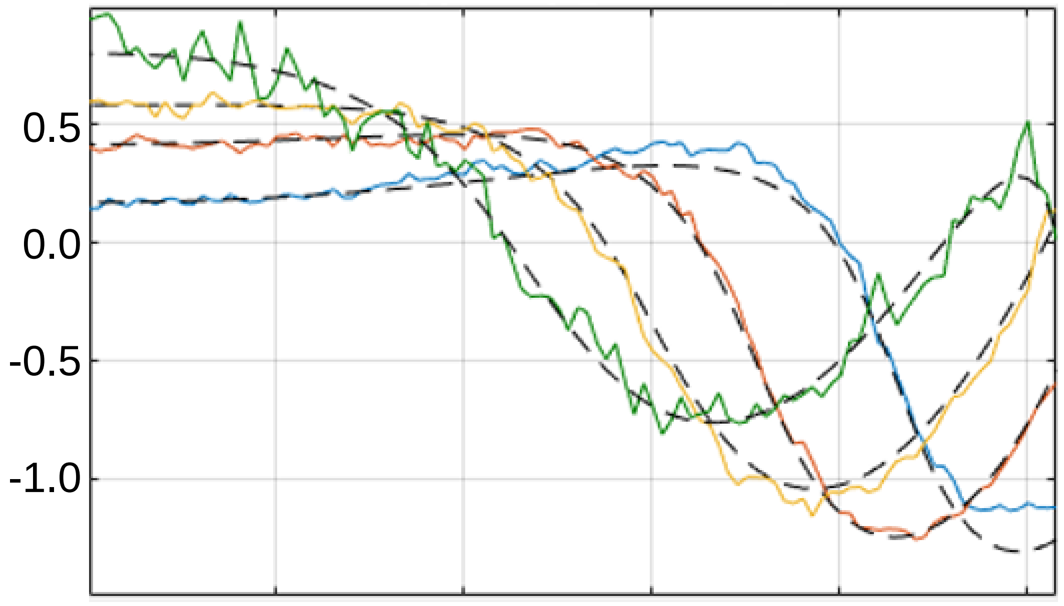
1045nm SiO_2

Signal Magnitude vs. AOI



769.2 nm
625.0 nm
526.3 nm
454.5 nm

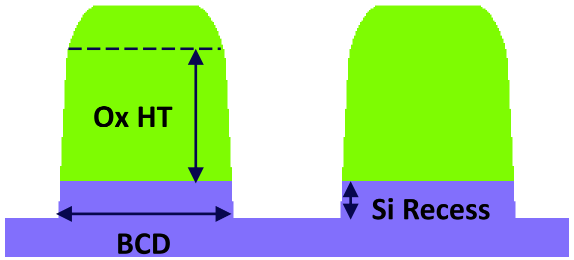
Signal Phase (radian) vs. AOI

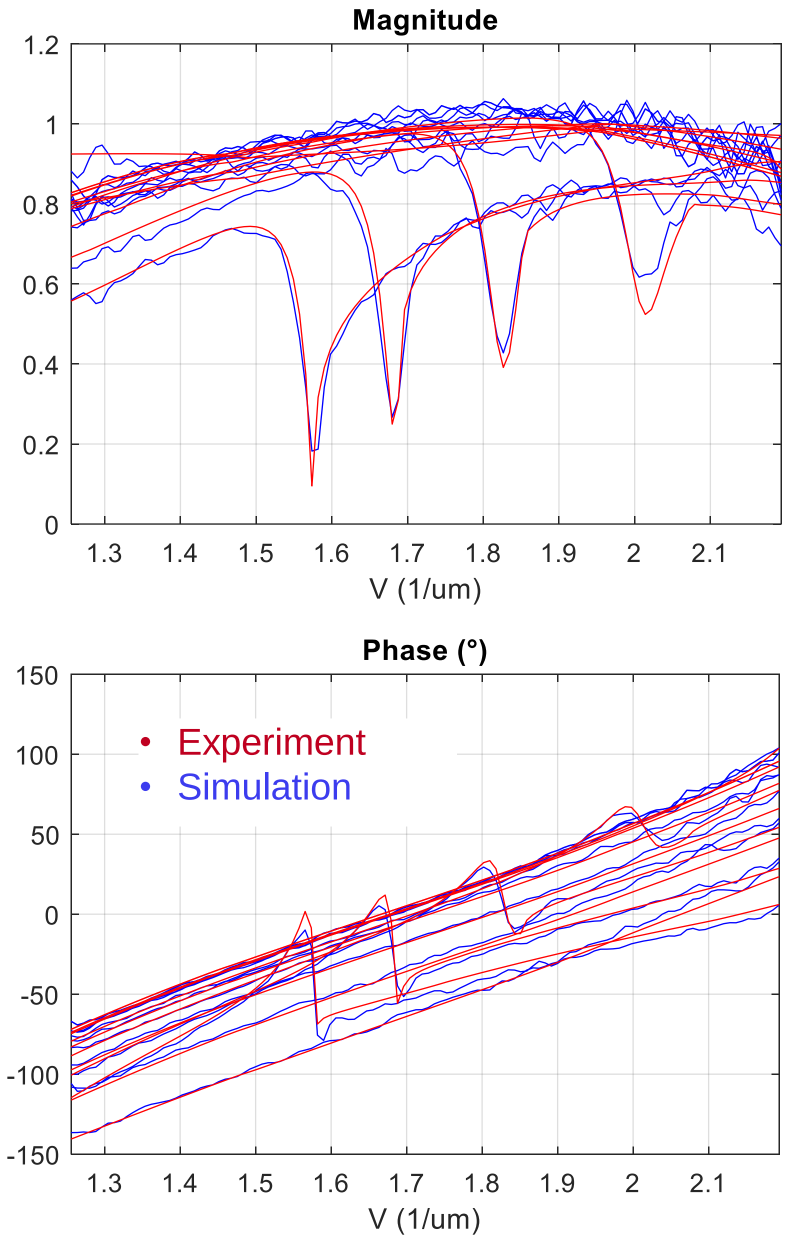


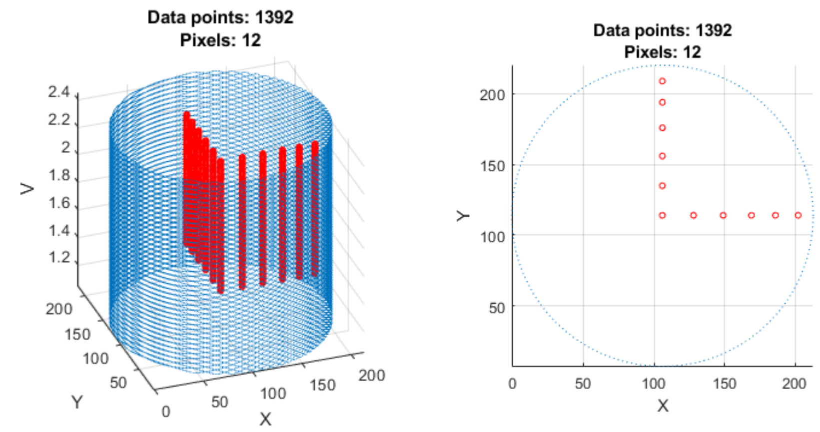
- Good use of phase data requires a common "zero phase" for all data points.
- Platform drift changes phase.
- The tool must be stable throughout the measurement.

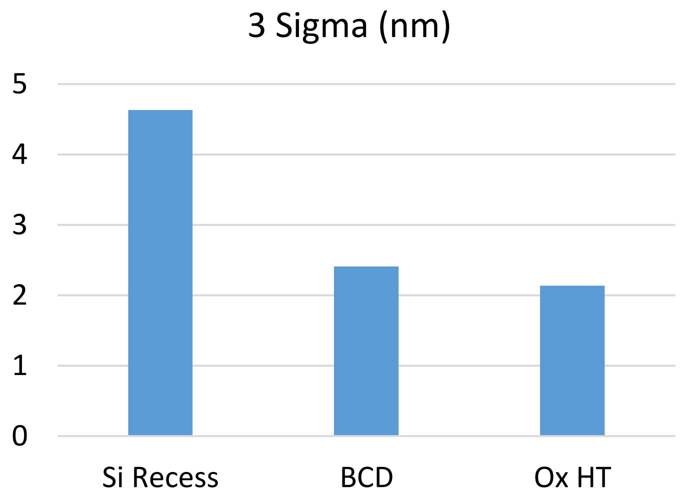
Measurement Case 1: 360nm pitch 1:1 Grating

Sampling plan









- Good use of phase requires wavelength-to-wavelength continuity.
- Platform stability is vital.

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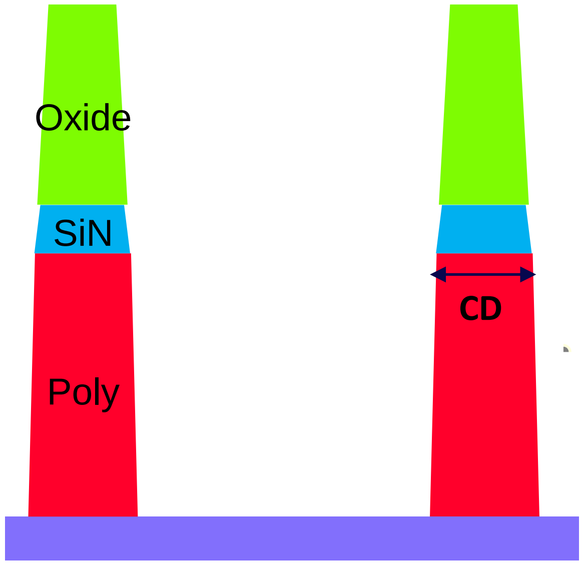
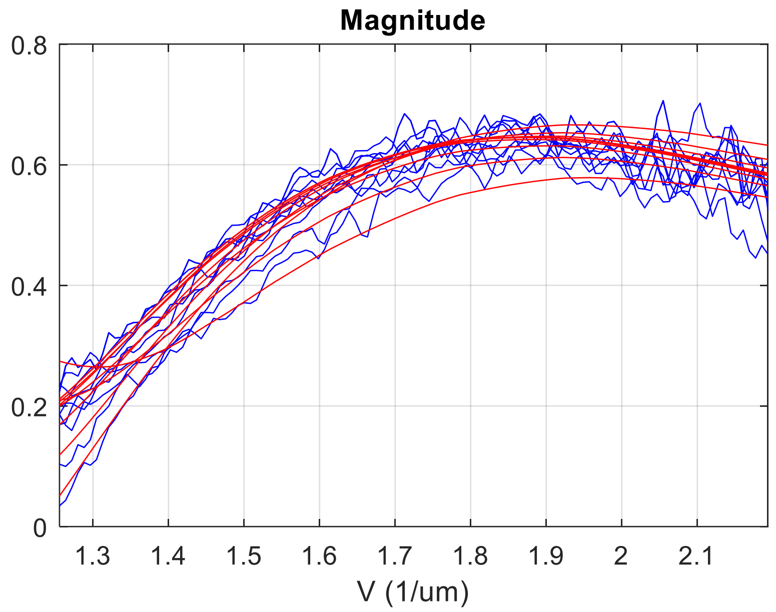
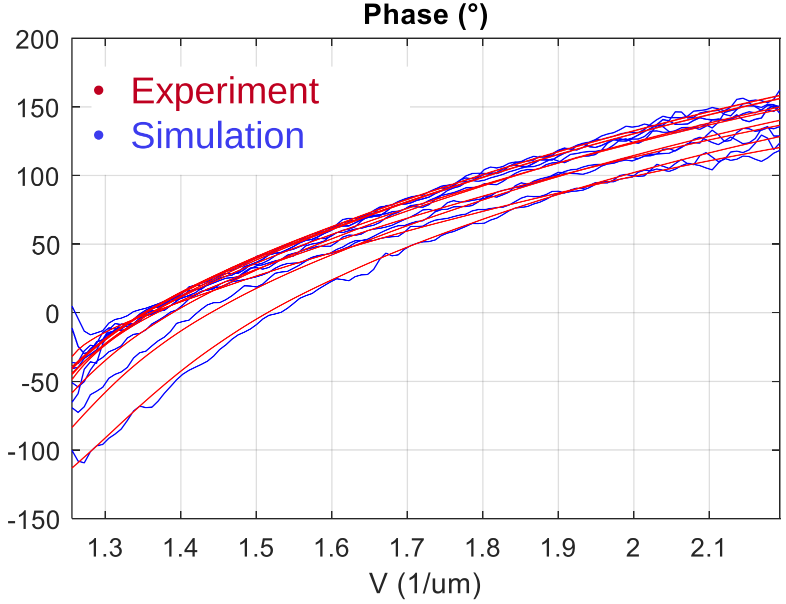
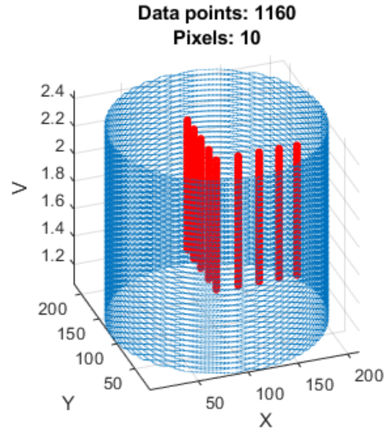
Measurement Case 2: Poly CD

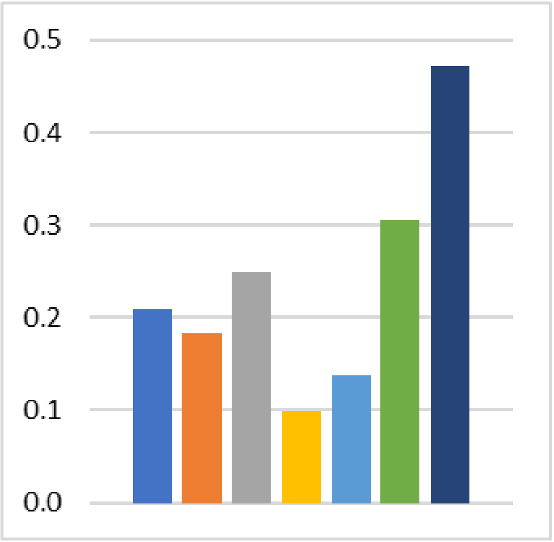






CD precision





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Vibration

$$I(z) = I_{DC} + I_{AC}(z) = S(k, AOI, Azimuth, t)(1 + C(k, AOI, Azimuth, z)e^{ikz})$$

Source intensity, tool

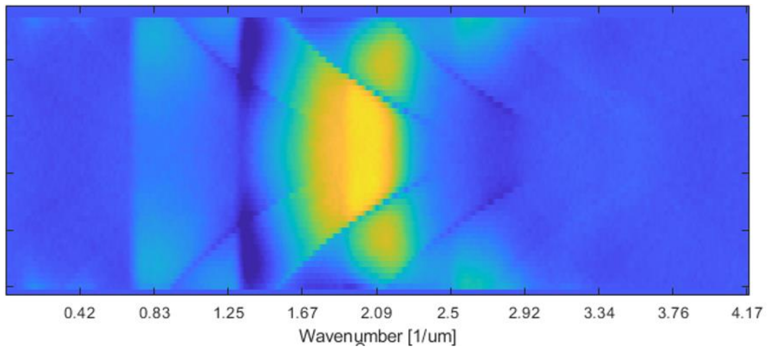
Signal envelope: sample

Modulation

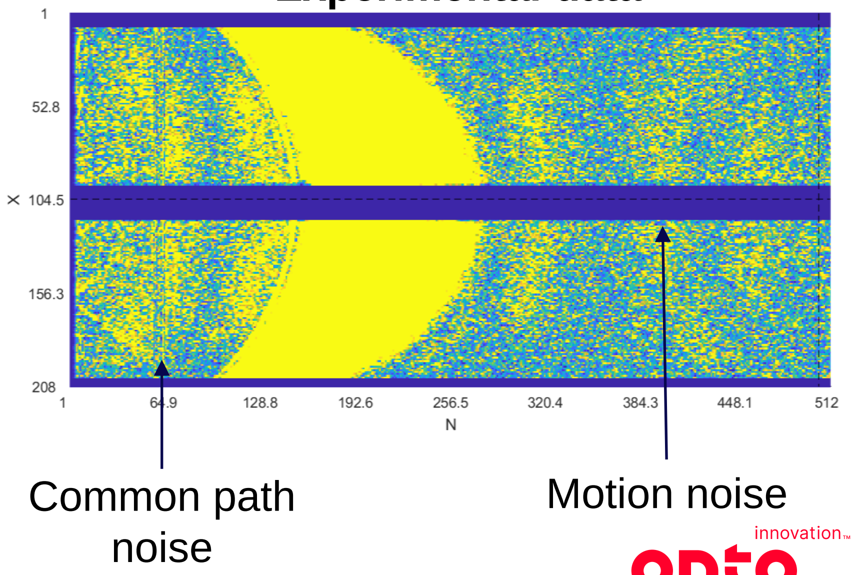
Single frequency noise: $z(t) = Vt + A\sin 2\pi f_z t$

Noise in signal: $\mathcal{FT}\left\{\frac{\partial C}{\partial z} dZ\right\}(k) = ikA\mathcal{FT}\{C\}(k \pm 2\pi f_z/V)$

Simulation: 7nm noise at 18Hz



Experimental data



- Common path noise gives rise to single frequency bands in the spectrum
- Motion noise inside the interferometer gives rise to side bands in the spectrum
- The noise contribution is independent of AOI
- The noise (f) frequency / side band is at $f_z/F\Delta$. (Frame rate F, sample spacing Δ; FΔ = V = scan speed).
- Noise is important if it appears inside the measured spectral range…
- … e.g. if $f_z = 0$! **Low frequency noise is important.**

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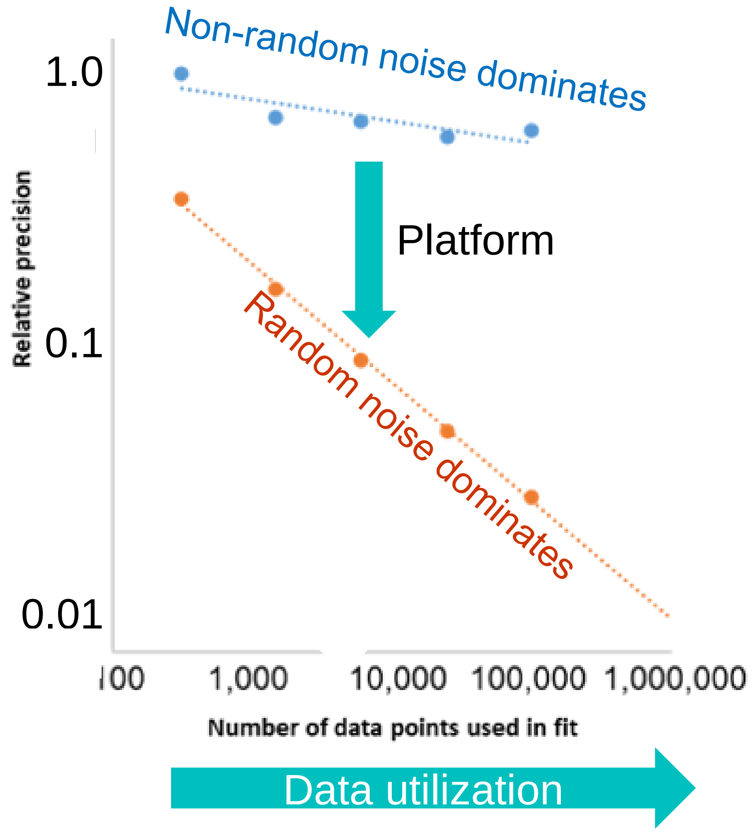
The Future #1: Increasing Data Utilization

- Dominant non-random noise:
  - low frequency vibration
  - focus error (Z stage capability).
- Random noise
  - Shot noise in camera
    - camera well depth,
    - light intensity
    - exposure time
  - High frequency vibration.
- If dynamic noise dominates then precision improves only slowly with increasing number of data points.

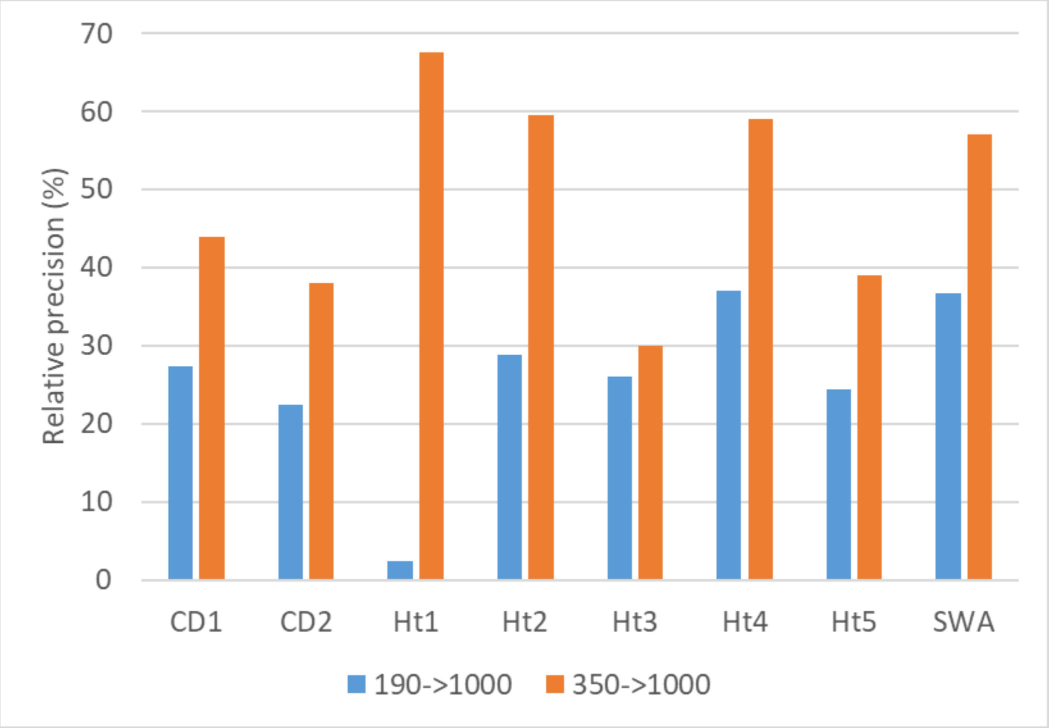
$$Precision \propto \sqrt{(dynamic\ noise)^2 + \frac{1}{N}(random\ noise)^2}$$

- If random noise dominates then for N data points:

$$Precision \propto \frac{1}{\sqrt{N}}$$

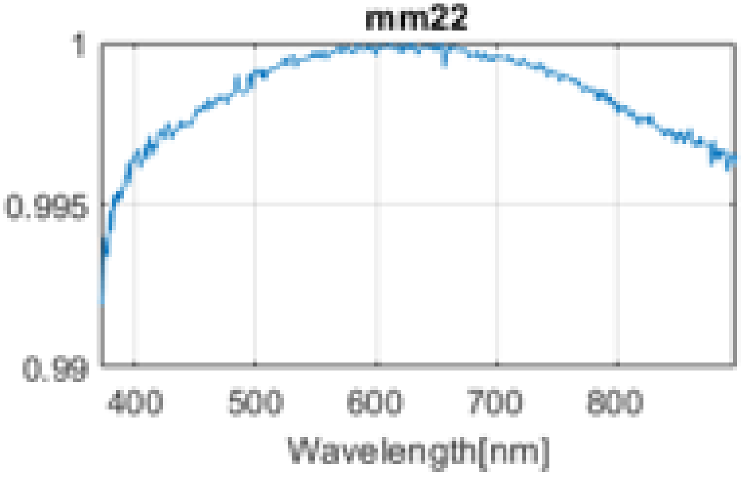


The Future #2: Shorter Wavelengths



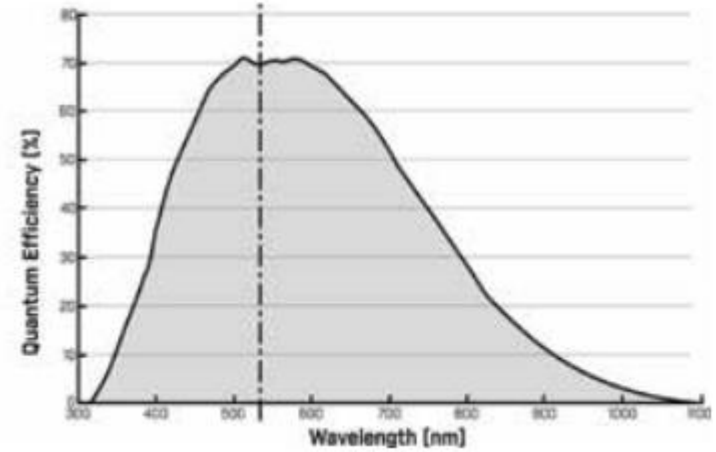
Precision using 190-1000 and 350-1000nm wavelength ranges relative to prevision using 450-1000nm

DRAM example.



Objective

Measured response



Sensor response

(manufacturer data)

Select components for shorter wavelengths.
Reflecting optics might be necessary.

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Conclusions

- Pupil plane interferometry is a viable OCD technique
  - Separation of incident angles enables a viable signal formation model.
  - Then use familiar model fitting methods to extract OCD parameters.
  - Requires reduction of the data to a manageable number of highly effective data points.
  - Phase data should be continuous throughout the data set.
    - The tool must be very stable during data acquisition.
- Probe size is much smaller than other methods.
- Significant improvement in measurement capability is feasible
  - By utilizing as much of possible of the acquired data cylinder.
  - Implies a change of strategy from simulation and fitting towards machine learning methods.

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Thank You

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ありがとう

Obrigado

Danke

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Merci

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