# Coherent EUV imaging and metrology with high-harmonic generation sources

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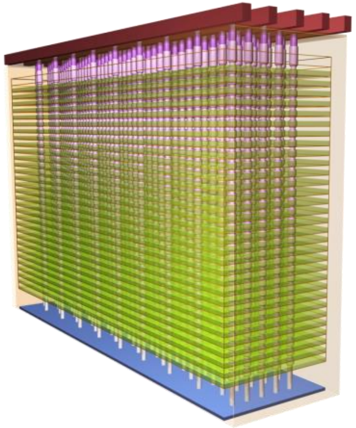
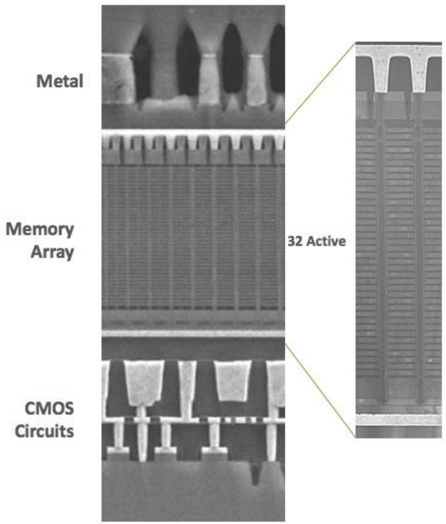
# Metrology challenges in nanolithography

- Next-generation lithographic devices are multilayer, often 3D structures
- Such devices may contain many different materials, many of which optically opaque
- Relative position of layers is crucial for device performance



3D NAND Structure




This raises interesting questions:

- How do you 'look through' opaque layers?
- What produces contrast on specific objects inside such a device?
- Non-invasive 3D nano-imaging of partially opaque structures?

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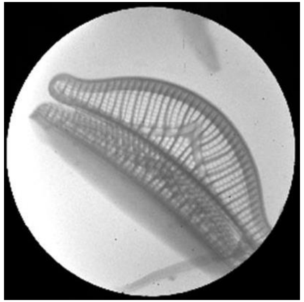
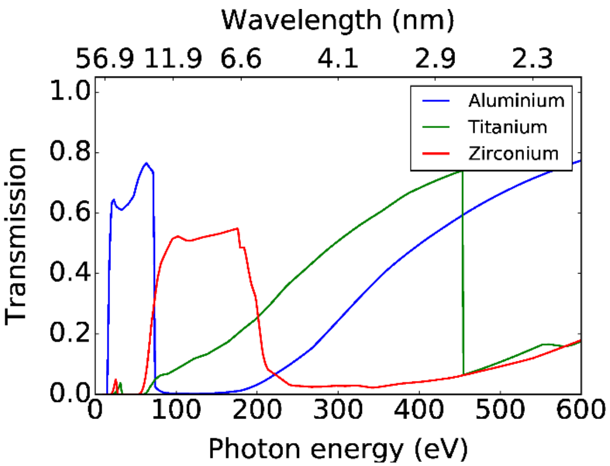
# Interesting properties of EUV radiation (for metrology)

1) Short wavelength → diffraction from nanoscale objects

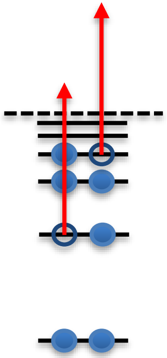


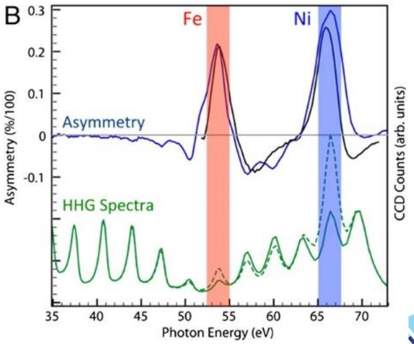
H. Stiel et al., MBI Berlin




2) Element-selectivity → most elements have specific spectral transmission windows

3) High photon energy → provides access to core levels






*S. Mathias et al. PNAS* ***109****, 4792 (2012)*

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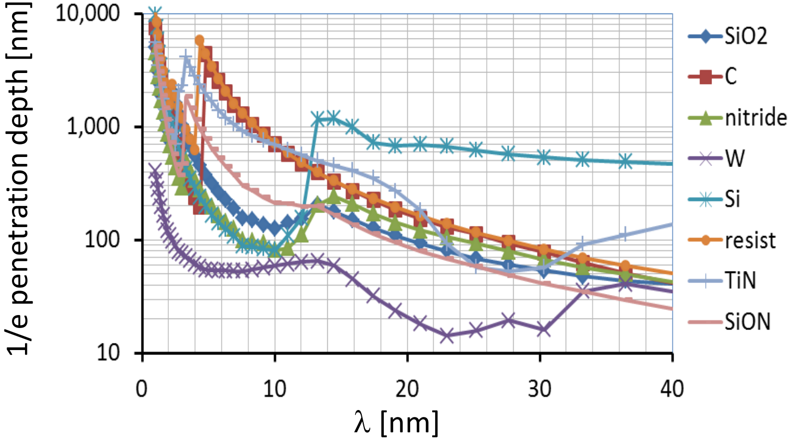
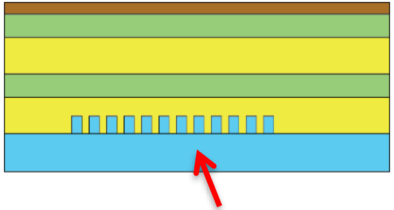
# Imaging and metrology with EUV sources

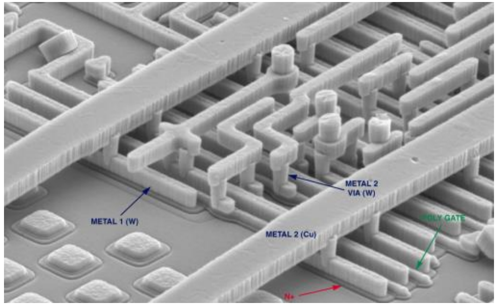
EUV-based metrology may have the capability to meet future wafer metrology needs:

- shorter wavelength → sensitive to smaller pitch structures
- ability to penetrate metals/semiconductors



Structure of interest (metrology mark, device structure)



- Applications in CD metrology, overlay on device, and imaging of non-periodic device structures
- Needs >µW flux in a coherent beam
- Optimum wavelength range 2-20 nm

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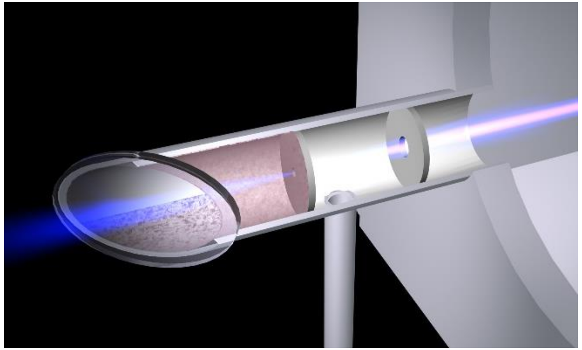
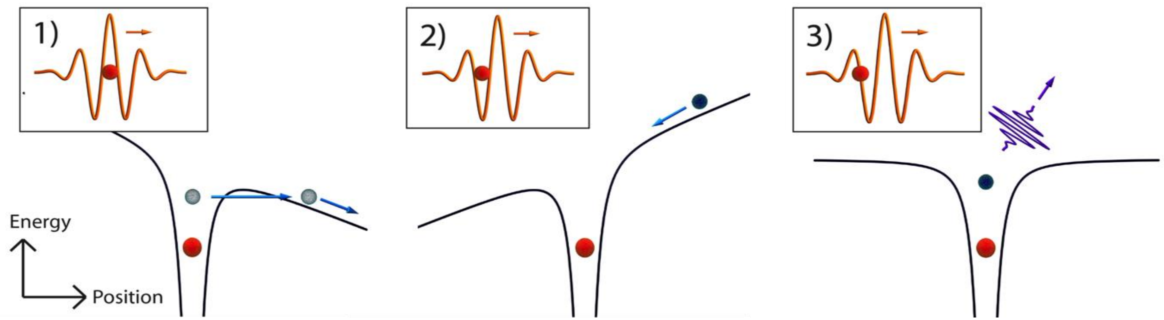
# High harmonic generation



Laser modifies Coulomb potential → electron tunnels and accelerates

Field changes sign → electron returns to the parent ion

Recollision, electron energy converted into EUV photon




- Compact source of fully coherent EUV radiation
- >nJ/pulse, ~kHz rep. rate → µW flux (sufficient for metrology apps)
- Process driven by an intense ultrafast laser source (mJ, fs pulses)

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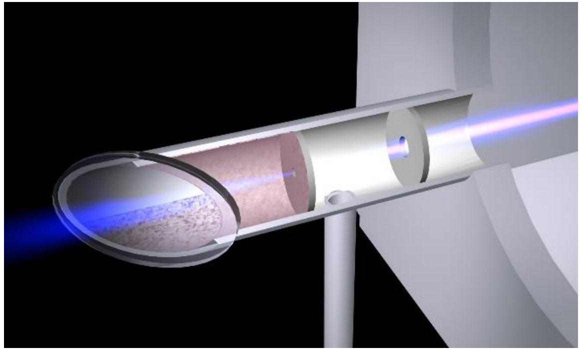
# High harmonic generation



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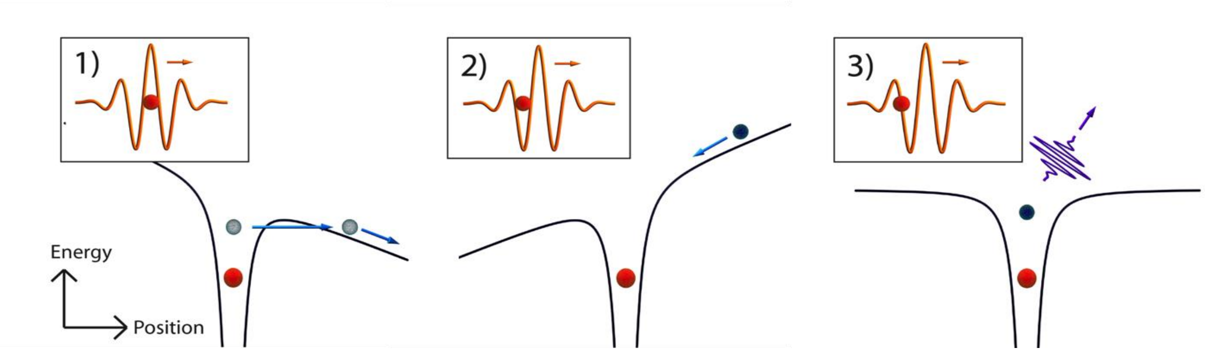
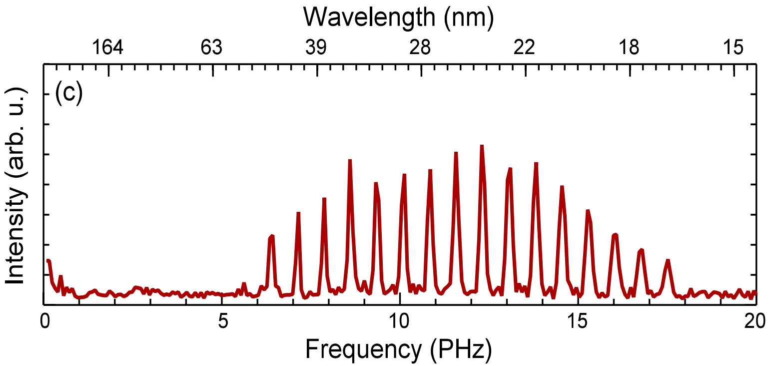
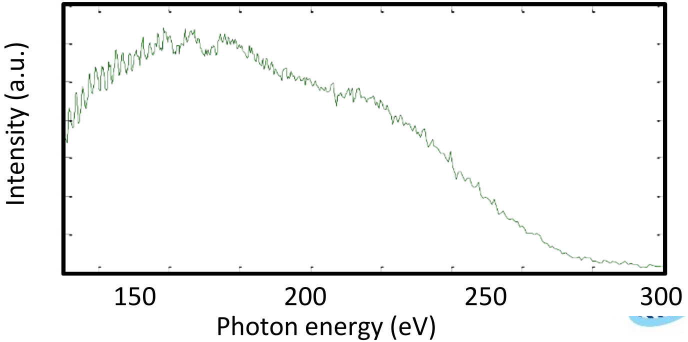



**Typical spectra:**

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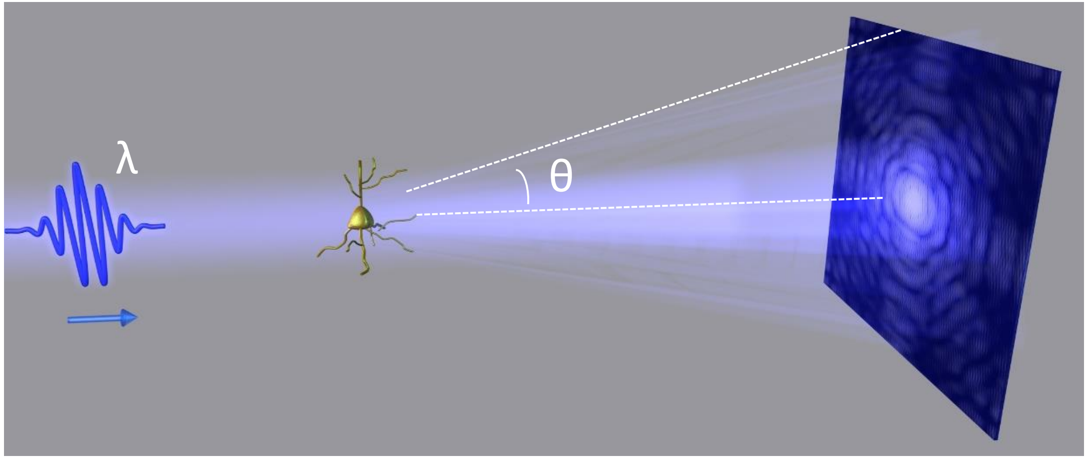
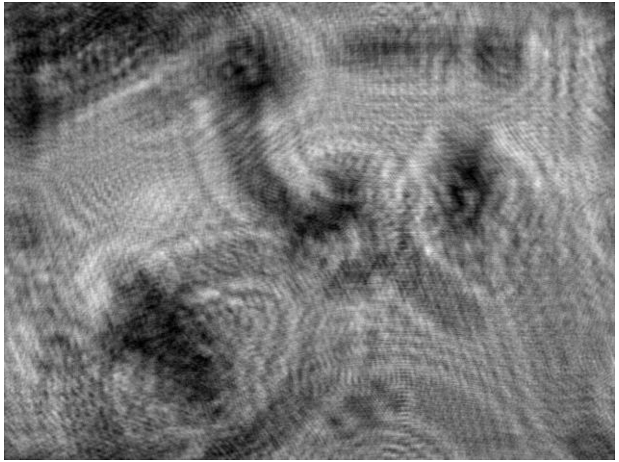
# Lensless coherent diffractive imaging

Numerical reconstruction of an object from a coherent diffraction pattern, instead of the use of optical components for image formation:



Measured diffraction yields intensity, phase also needed for image reconstruction

→ The challenge is to retrieve the missing phase information.

- Resolution = $\lambda / 2 \sin\theta$
- High spatial and temporal coherence important.

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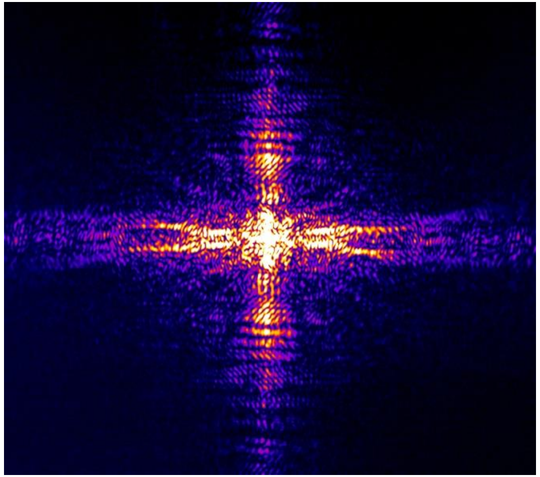
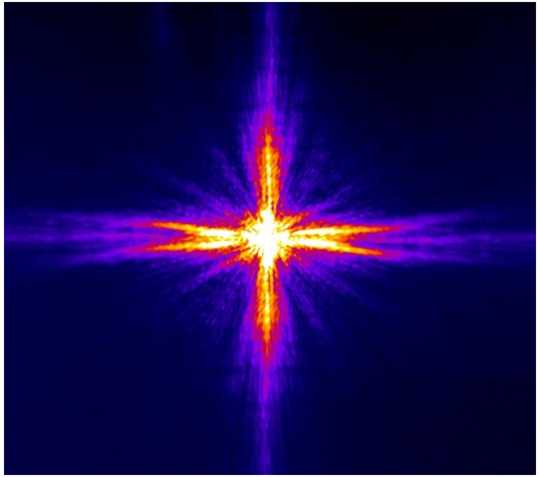
# Bandwidth limitations in lensless imaging

- Diffraction angle is directly proportional to wavelength.
- Broadband sources lead to blurred diffraction patterns:

Monochromatic:



Broadband:



- Limits the resolution, in extreme cases prevents image reconstruction.
- Spectral filtering is possible, but at the cost of serious flux reduction.

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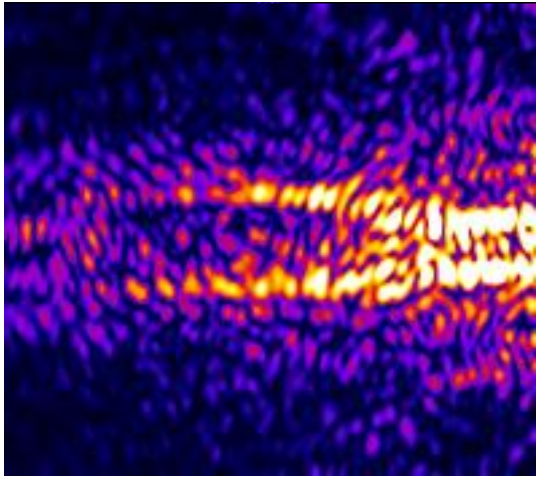
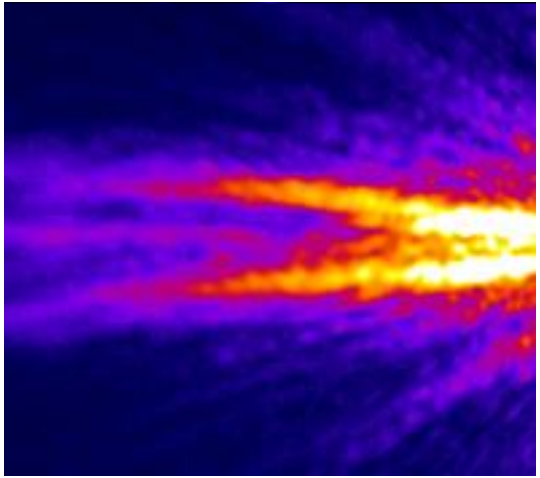


Broadband:



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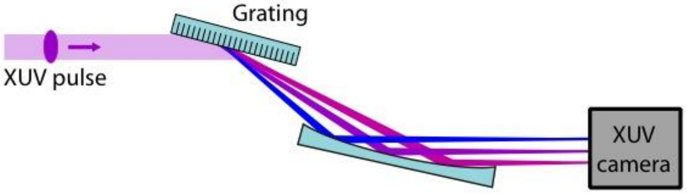
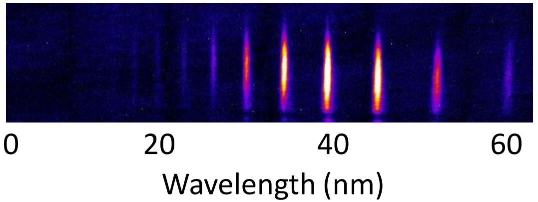
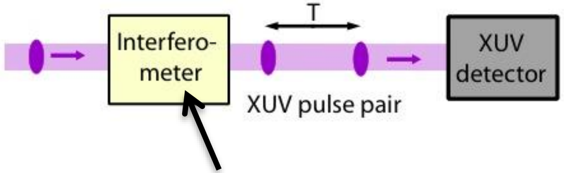
# EUV spectroscopy

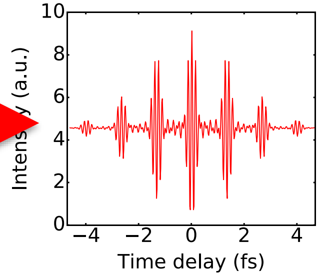
**Diffractive grating-based spectrometer**: use diffraction to disperse different wavelengths over a spatial axis.

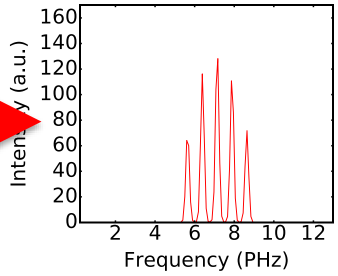



**Fourier-transform spectroscopy**: measure temporal coherence function and retrieve frequency information by Fourier transform.




Sub-λ stability essential!

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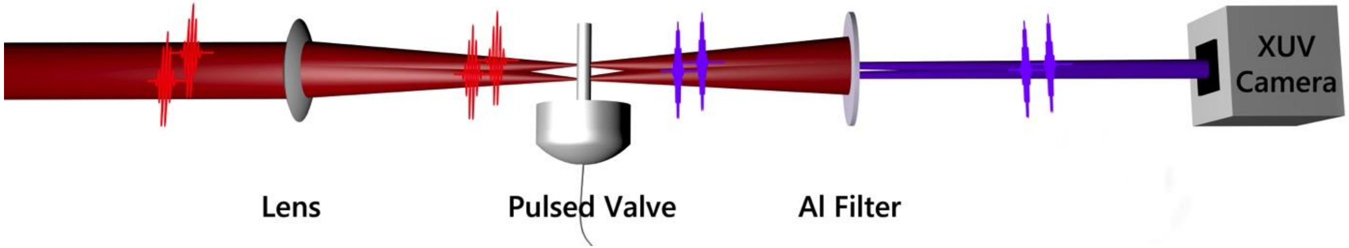
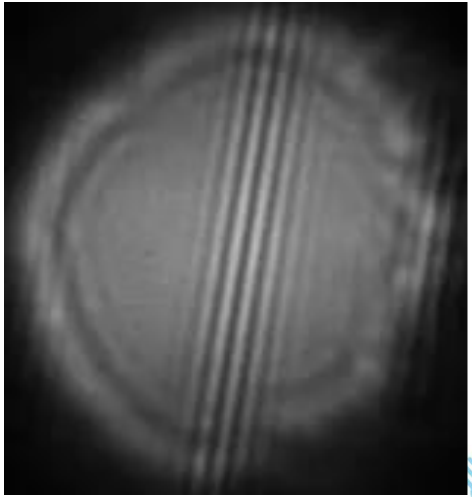
# EUV interferometry

HHG setup combined with ultra-stable common-path interferometer:




- HHG in Argon with >1 mJ ~20 fs pulses
- Individual pulses should not influence each other during the HHG process → spatially separated HHG zones.
- Collinear beams, overlap after finite distance due to beam divergence.



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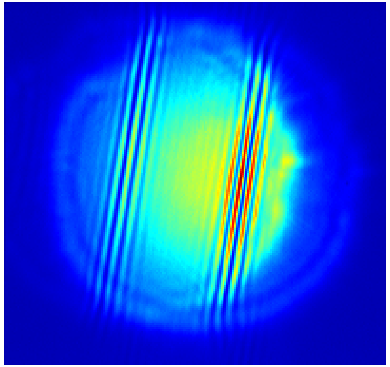
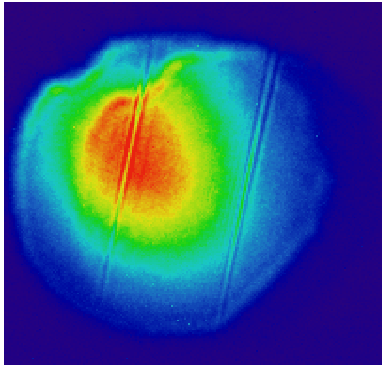
# HHG Fourier transform spectroscopy

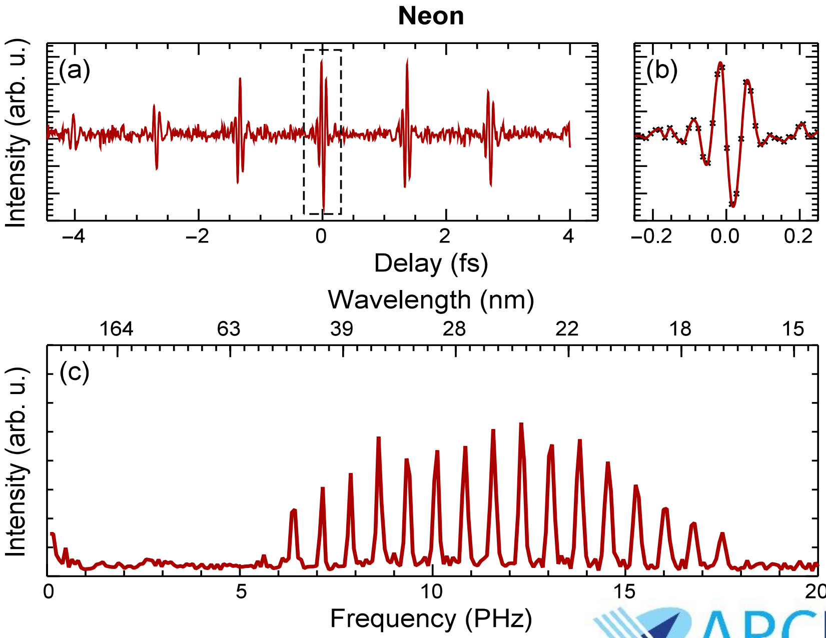
- Fourier transformation of the time delay scan on a single pixel yields the spectrum at the location of that pixel.
- Linear autocorrelation of two HHG beams yields coherence length.
- Measured 0.8 as RMS timing stability between the two pulses (0.25 nm optical path length).

HHG-FTS in Argon:



HHG-FTS in Neon:

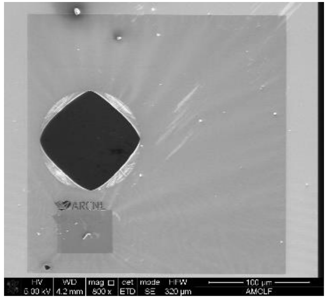


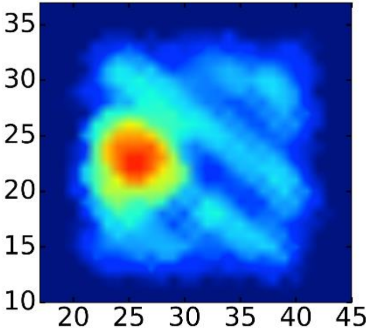


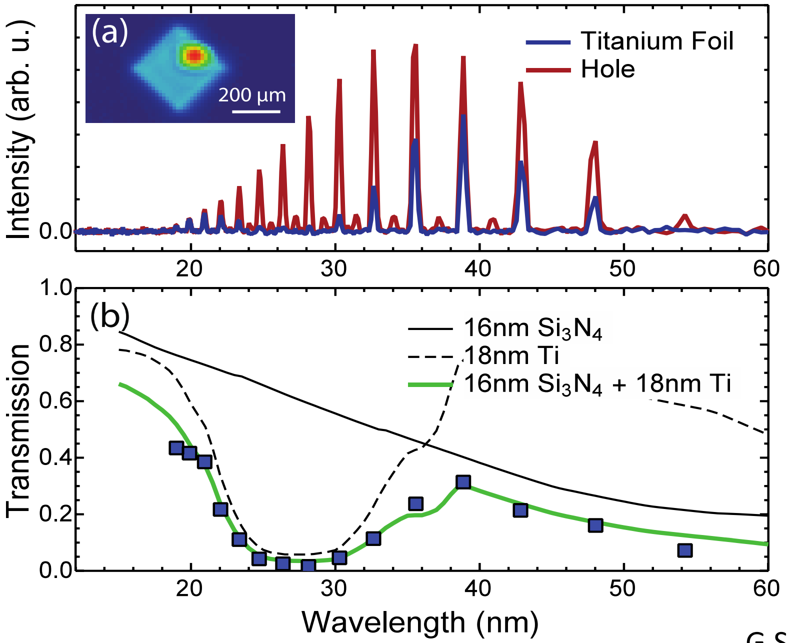

G.S.M. Jansen et al., Optica **3**, 1122 (2016)

# Spatially resolved EUV spectroscopy

Titanium layer on 250x250 µm silicon nitride foil with a 50 µm reference aperture:






G.S.M. Jansen et al., Optica **3**, 1122 (2016)

- Detecting Neon HHG spectrum on each CCD pixel using FTS
- Measurement of the transmission spectrum in the 17-55 nm range

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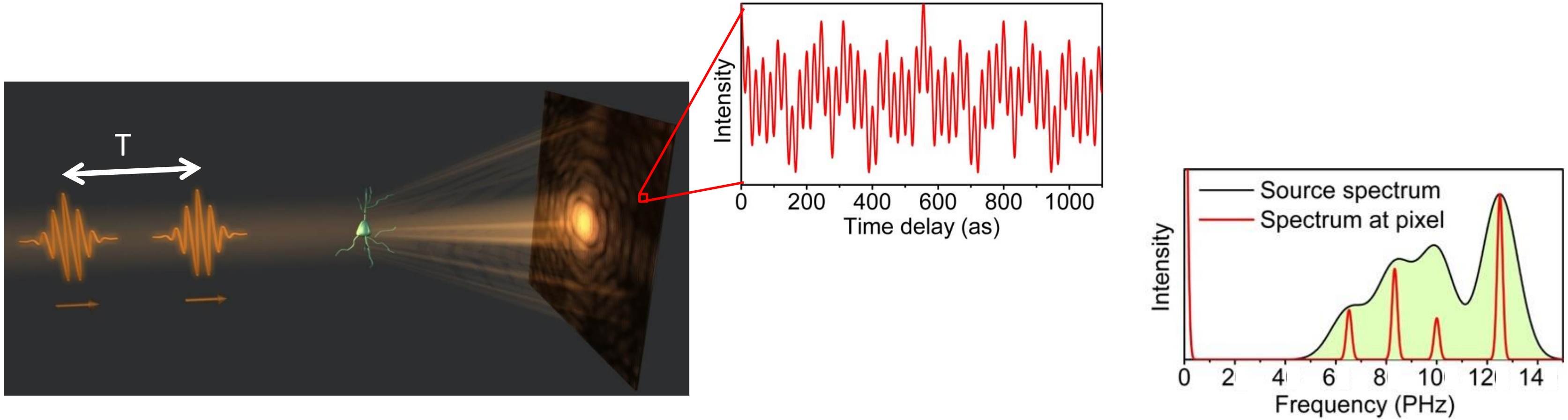
# Two-pulse Fourier-transform imaging

- Combination of imaging and Fourier transform spectroscopy
- On each CCD pixel, a Fourier-transform spectrum is recorded of the light diffracted onto that specific pixel.




- Allows reconstruction of ‘monochromatic’ diffraction patterns for all spectral components
- The full spectrum is used throughout the entire measurement.

Witte, Tenner, Noom, Eikema,
Light: Sci. Appl. **3**, e163 (2014)

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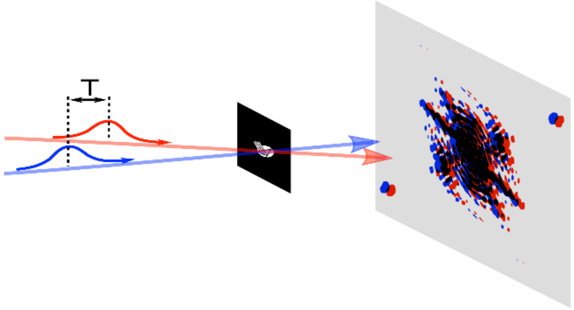
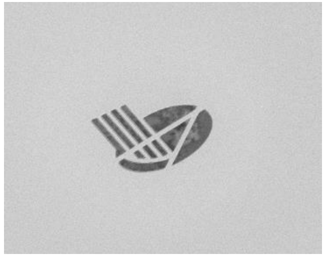
# High-resolution, spectrally resolved EUV imaging

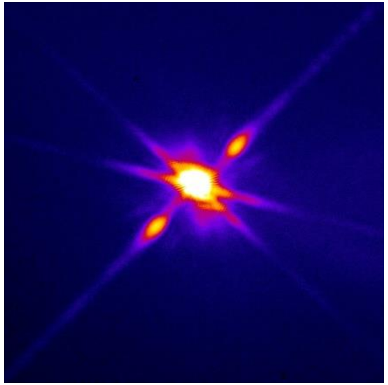
- Fourier transform spectroscopy retrieves well-defined monochromatic diffraction patterns
- Image reconstruction from these patterns yields diffraction-limited images



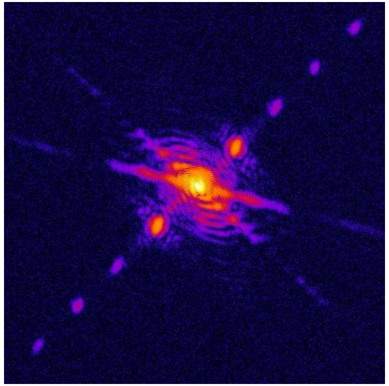

SEM image:



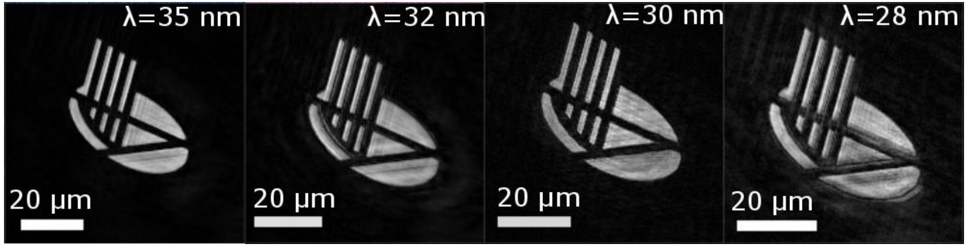
Broadband diffraction:



Reconstructed pattern
(from FTS)at λ=33 nm:



Retrieved object images for different harmonics:




G.S.M. Jansen, A. de Beurs, K. Liu, K.S.E. Eikema, S. Witte, Opt. Express **26**, 12479 (2018)

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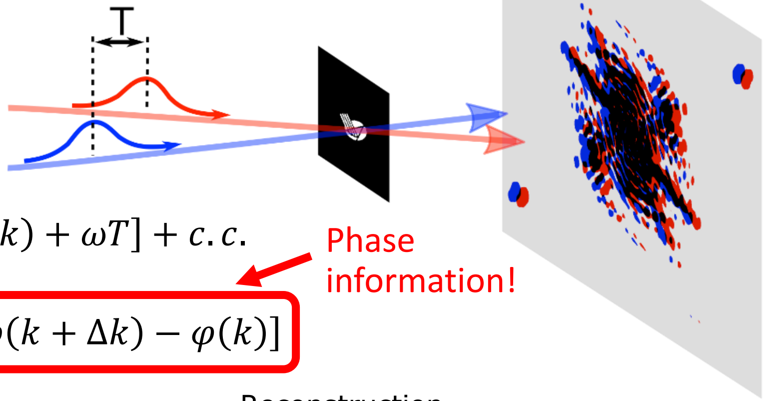
# Diffractive shear interferometry

Our diffraction pattern is produced by two displaced coherent beams, so we measure:




$$I = |E(k) + E(k + \Delta k)|^2$$
$$= A(k)^2 + A(k = \Delta k)^2 + A(k)A(k + \Delta k)\exp[i\varphi(k + \Delta k) - \varphi(k) + \omega T] + c.c.$$

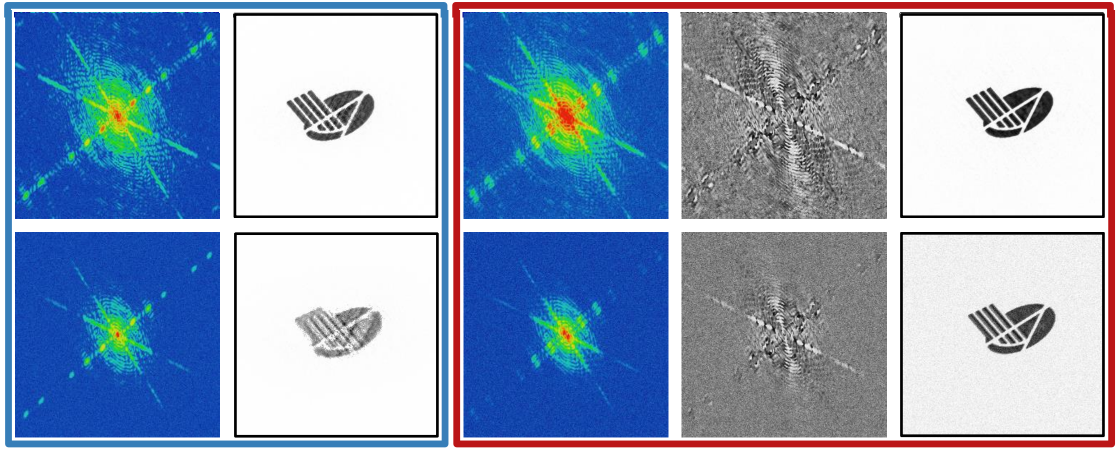
Phase information!

After FTS and selecting one spectral component we retrieve:

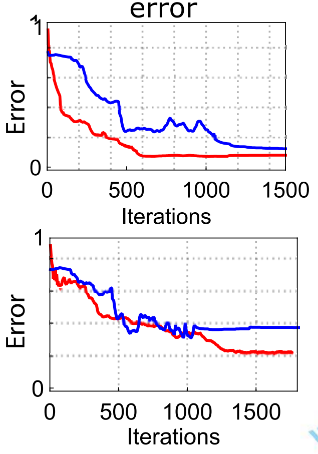
$$I = A(k)A(k + \Delta k)\exp[i\varphi(k + \Delta k) - \varphi(k)]$$

Single-beam CDI

Diffractive Shear Interferometry



Reconstruction error

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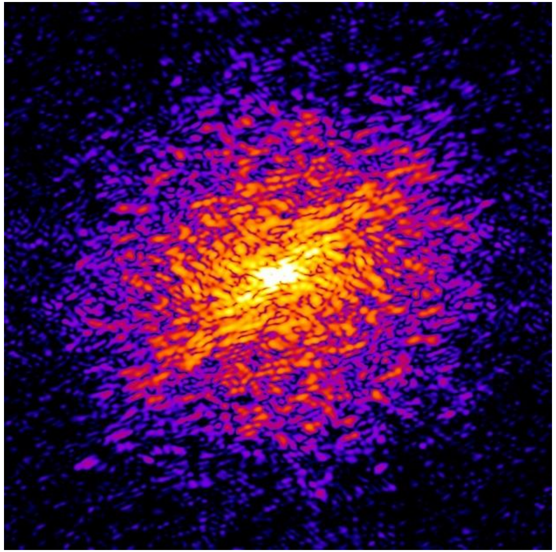
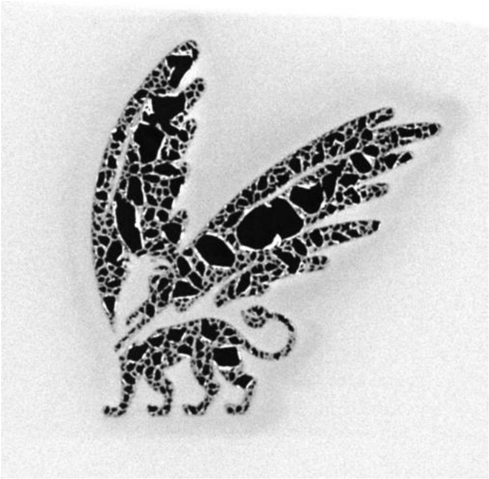
# EUV imaging of more complex objects

’Grayscale’ intensity objects lead to more complex diffraction patterns:

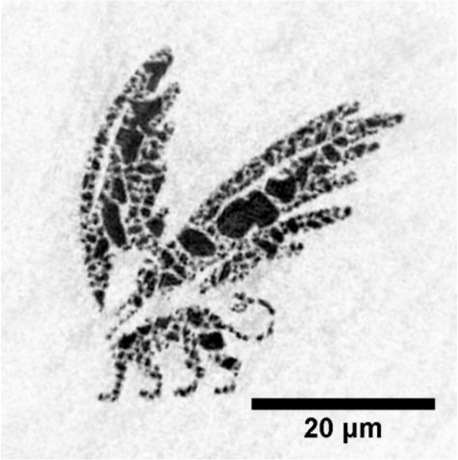
Measured diffraction pattern ($\lambda$ =30 nm):



SEM image:



Reconstructed image (30 nm):




- Good contrast reconstruction, both amplitude and phase.
- Resolution near diffraction limit of 0.25 $\mu$m

G.S.M. Jansen, A. de Beurs, K. Liu, K.S.E. Eikema, S. Witte,
Opt. Express **26**, 12479 (2018)

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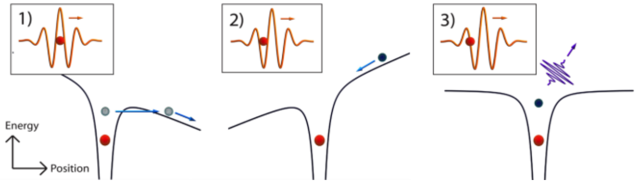
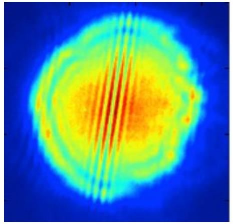
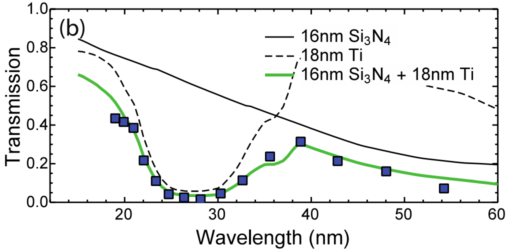
# Conclusions

High harmonic generation is a compact and versatile source of coherent EUV radiation for metrology

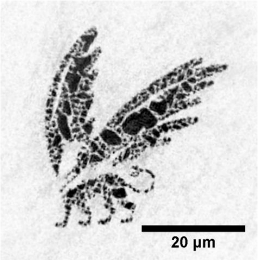


- EUV-based metrology is a potentially interesting tool for litho applications




- The broad bandwidth of HHG sources allows spectroscopic characterization (identification) of materials




- Spectrally resolved lensless EUV imaging is possible through coherent diffractive (lensless) imaging techniques

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