Transmission and Reflection-Mode Tabletop Imaging with 13 nm Illumination via Ptychography CDI

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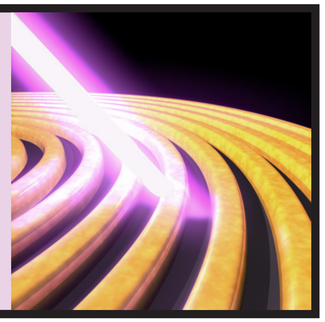
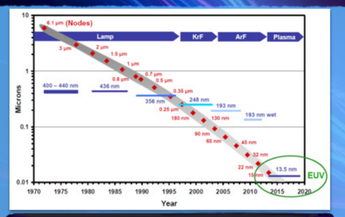
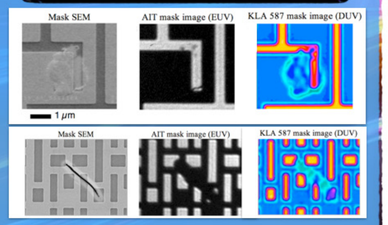
Goal: Peform imaging using ~13 nm illumination produced by high harmonic generation (HHG) in both transmission and reflection geometries using ptychographic coherent diffraction imaging.



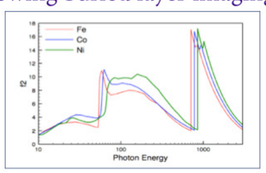


Actinic inspection of EUV masks is an important capability for defect detection



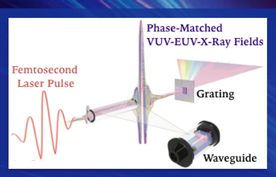
EUV light is an ideal probe for imaging the nano world

- Extreme Ultraviolet (EUV): λ ~10–100 nm
- Ultrahigh resolution imaging within the diffraction limit (~λ/2)
- Elemental contrast, chemical specificity → spectromicroscopy
- EUV penetrates thick objects allowing buried layer imaging

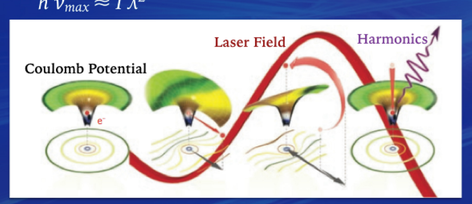


Mochi *et al.*, *SPIE* **7636**, 76361A (2010)

Dan Armbrust, SEMATECH, Litho Forum 2010



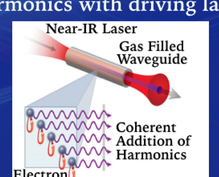
- Laser field distorts coulomb potential
- e^- tunnel ionizes & accelerates in laser field
- Recombination → harmonics emitted up to $h\,\nu_{max} \approx I\,\lambda^2$



Why HHG?

- Tabletop
- Coherent
- Ultrafast temporal resolution

Phase Matching:
Match phase velocity of harmonics with driving laser



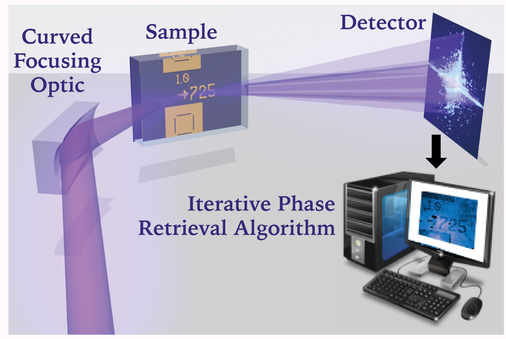
Tabletop EUV Source: High Harmonic Generation (HHG)

McPherson *et al.*, *JOSA B* **4**, 595 (1987)
Rundquist *et al.*, *Science* **280**, 1412 (1998)

Bartels *et al.*, *Science* **297**, 376 (2002)
Zhang *et al.*, *Optics Letters* **29**, 1357 (2004)

Experiments

Coherent Diffraction Imaging: *Lensless*



- Diffraction-Limited Resolution
- Amplitude & Phase Contrast

Apparatus:

Ti:Sapphire Oscillator

Modelocked, 790 nm, 80 MHz, 0.45 W

Reflection: Regenerative Amplifier

38 fs, 3 mJ pulses, 60 nm bandwidth, 3 kHz, 8.5 W

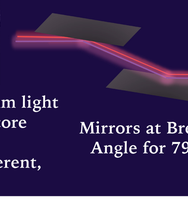
Transmission: Ring Amplifier

23 fs, 2 mJ pulses, 80 nm bandwidth, 3 kHz, 6 W

HHG Source

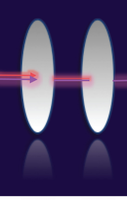
Generates 12.7 nm or 13.5 nm light ~600 torr He in hollow-core glass fiber ~10^9 photons/s (nW) coherent, single harmonic flux

Rejecter Mirrors



Mirrors at Brewster's Angle for 790 nm

ZrO_2 Filter(s)

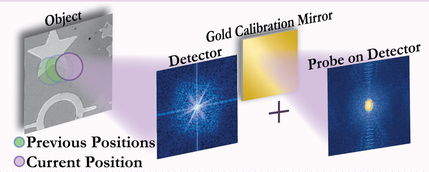


Microscope Chamber

Contains multilayer mirrors, focusing optic, sample & camera

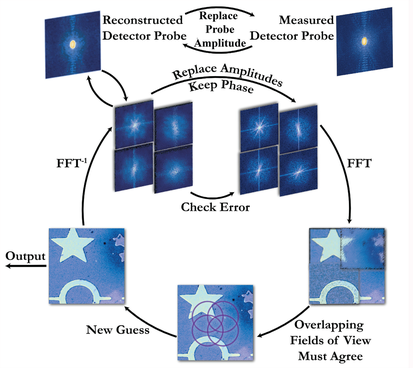
Data Collection:

Diffraction patterns from overlapping, area-by-area scan of sample + image of undiffracted illumination on detector.

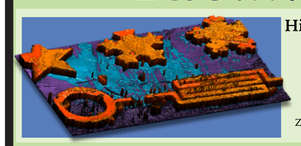


Reconstruction:

- Ptychography:
  Robustly deconvolves object and illumination (probe) using redundant info from scan with overlap. Returns amplitude & phase image for each.
- Modulus Enforced Probe (MEP):
  Impose amplitude constraint for probe on the detector to improve probe guess & algorithm convergence.
- MEP can yield RAPTR CDI images:
  Reconstructed Absolute Phase-Diverse Transmissivity/Reflectivity CDI
  Quantitative CDI algorithm that returns absolute reflectivity or transmissivity intensity image by enforcing correct probe power each iteration. Yields depth-sensitive chemical composition information.



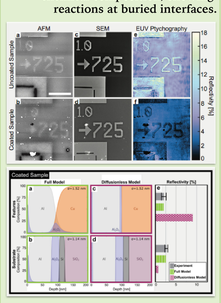
Results:



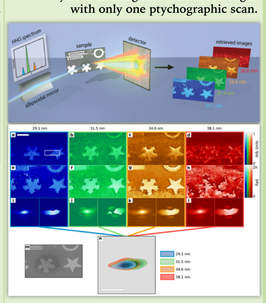
High NA Reflection-Mode Ptychographic Imaging:
40nm transverse resolution
0.5mm axial resolution

Zhang *et al.*, Ultramicroscopy 158, 98 (2015)
Adams *et al.*, Laser Focus World 38, (2015)

Quantitative Buried Layer Imaging:
RAPTR CDI yields depth-dependent chemical composition, showing reactions at buried interfaces.



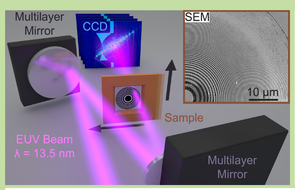
Hyperspectral Imaging:
Multimode ptychography allows multiple harmonics to illuminate the sample; yields an image for each wavelength with only one ptychographic scan.



Porter & Shanblatt *et al.*, Nano Letters 16 (2016)

Zhang *et al.*, Optics Express 24, (2016)

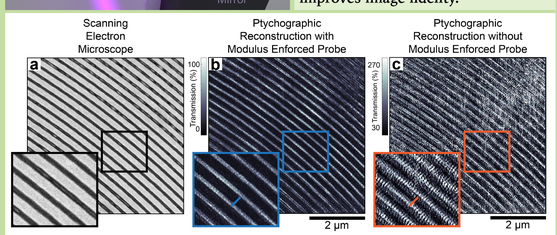
Previous Work (λ=30 nm)

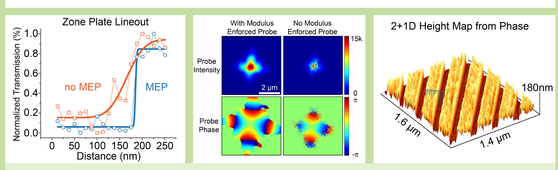


Lineouts, Power Spectral Density & Phase Retrieval Transfer Function all Support 12.6 nm Resoution

This is the ***1st sub-wavelength resolution EUV CDI*** image with any source!

Modulus Enforced Probe dramatically improves image fidelity.

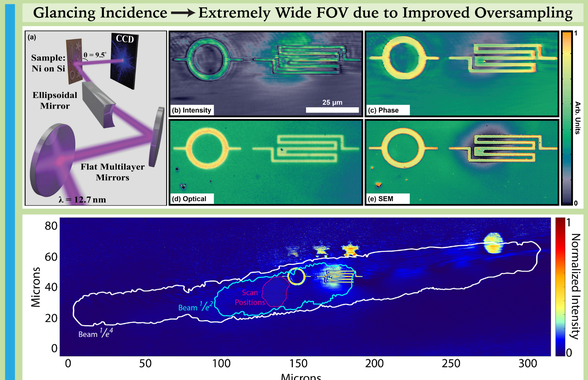


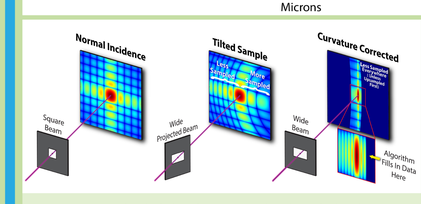


Gardner *et al.*, Nature Photonics (2017), in press. (Published online March 20th)

λ=13.5 nm Transmission Results: 1st EUV Sub-λ Resolution

Glancing Incidence → Extremely Wide FOV due to Improved Oversampling





Benefits of Glancing Incidence:

All materials reflective → Microscope a general tool. This is the 1st 13nm reflection mode image of a general sample not fabricated on an EUV mirror.

Conical diffraction improves oversampling to yield wide field of view without a long scan. *42x the area scanned by the beam center reconstructs!*

Porter and Tanksalvala *et al.*, Proc. SPIE Adv. Lithography (2017).

λ=12.7 nm Reflection Results: 1st ~13nm Tabletop Reflection