Paul Scherrer Institute

Evaluation of resist performance with EUV interference lithography

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Outline

- EUV interference lithography
  - Basics of EUV-IL
  - XIL-II: EUV-IL @ PSI
  - Versatile and high-resolution patterning with EUV-IL
- Evaluation of EUV-CARs
- First patterning results with BEUV
- Conclusions and outlook

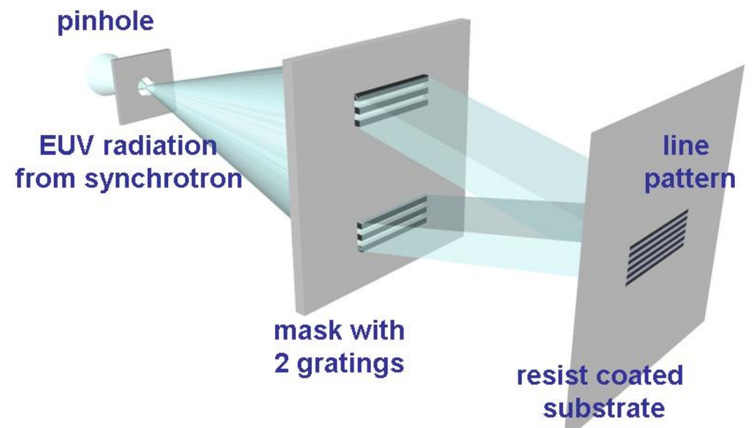
EUV Interference Lithography

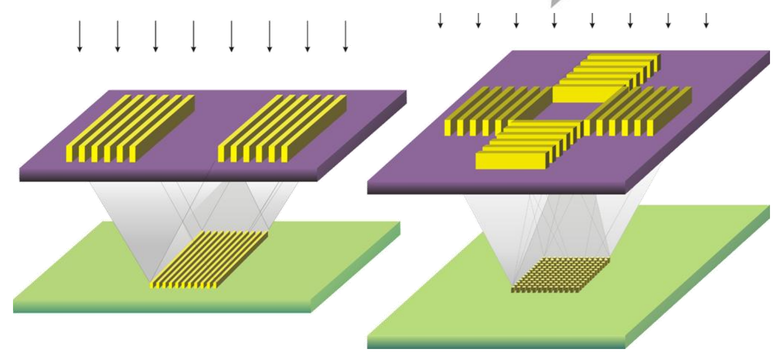
XIL-II beamline as Swiss Light Source (SLS)

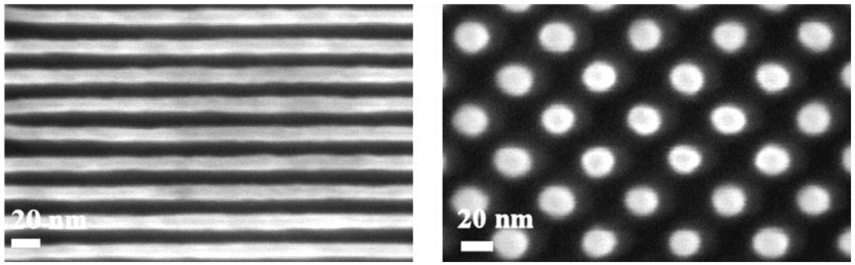
- EUV lithography: 13.5 nm wavelength
- Undulator source:
  - Spatially coherent
  - Temporal coherence: $\Delta\lambda/\lambda$=4%
- Diffractive transmission gratings: Metal gratings written on Si_3N_4 membranes with EBL
- diffracted beams interfere
- interference pattern printed in resist

Advantages:

- No proximity effect (e^{-} mean-free-path < 1-3 nm)
- No depth of focus: Mask-to-wafer = 1-10 mm
- High resolution:
  - Theoretical limit= 3.5 nm
  - Current limit < 10 nm (world record in photon based lithography)
- Large area: up to 5x5 mm^2
- Step and repeat: up to 80x80 mm^2 with stitching
- High throughput: typically 10 s: 10’000x e-beam
- Quality, reproducibility: enabling industrial operation
- Versatile structures







11 nm hp lines and 19 nm hp dots exposed in HSQ

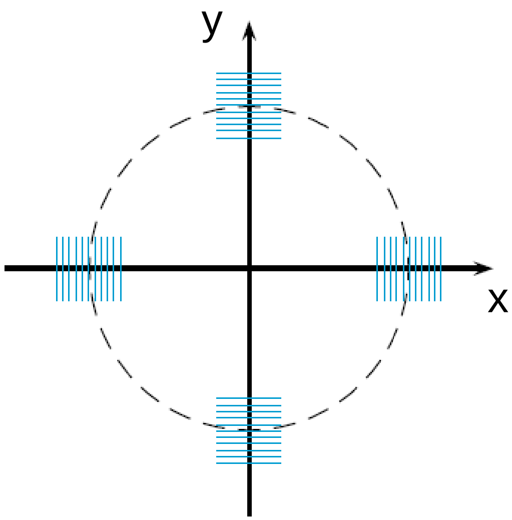
V. Auzelyte et al., J. Micro/Nanolith. MEMS MOEMS 8, 021204 (2009).

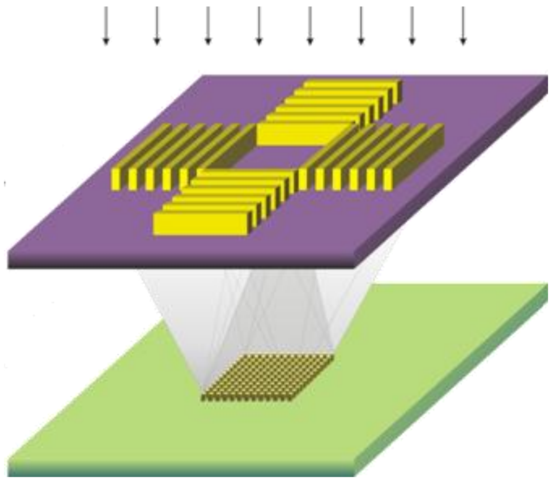
XIL-II facility

- On-site clean room:
  - Spin-coater, wet-bench, hot-plates, microscope, developer, optical thickness measurement
  - In clean room environment with amine filters.

2D periodic patterns by multiple beam interference

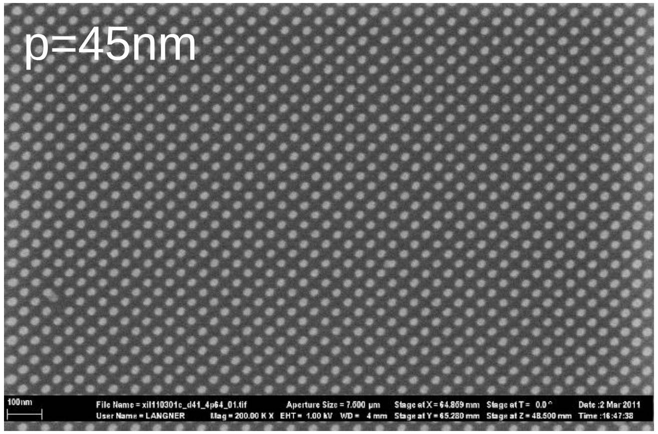
- Two-dimensional periodic patterns for 3-, 4- and 6-beam interference

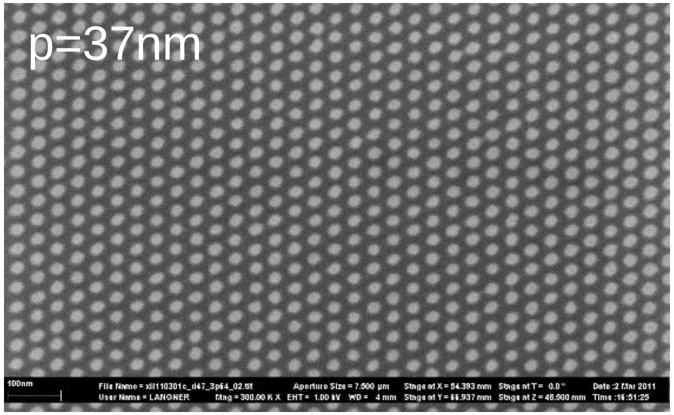




4- beam

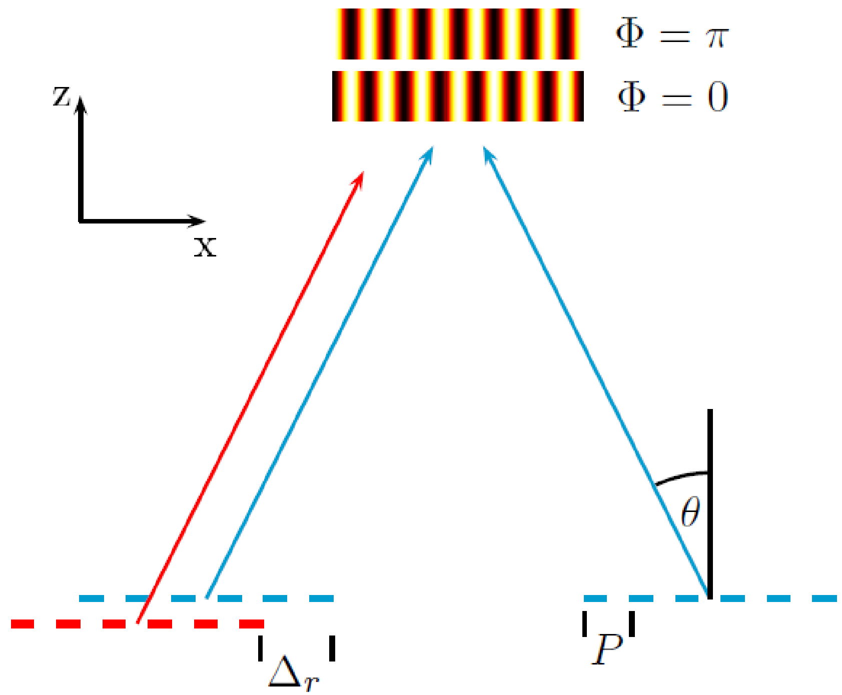
3-beam





Phase-control

- Grating positions determine relative phase between interfering waves
- Shift Δ_r perpendicular to the grating lines enables phase control by additional phase shift Φ



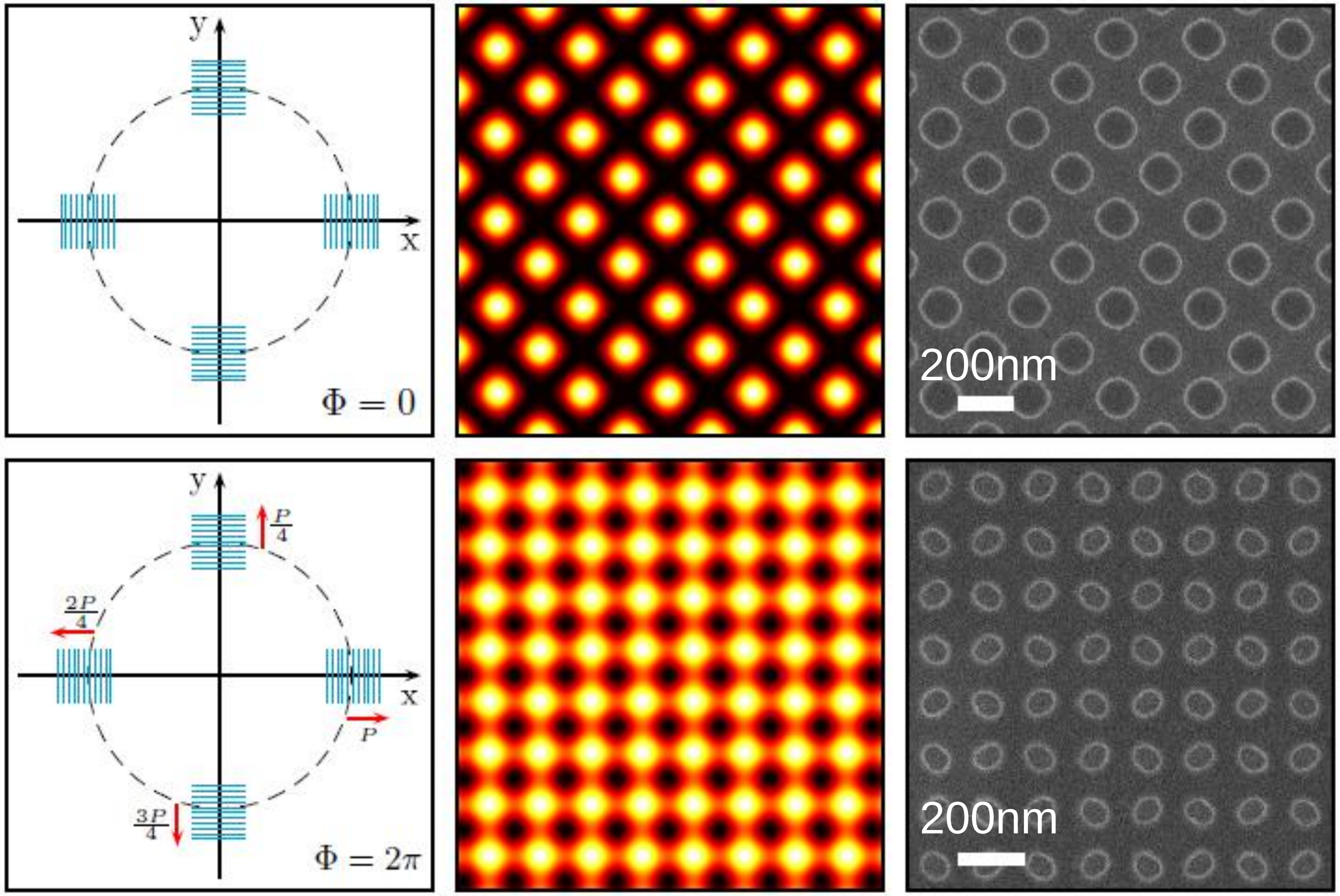
$$\sum_n^N U_{0,n} \exp(i(k_{x,n}(x-\Delta_{x,n})+(k_{y,n}(y-\Delta_{y,n})+k_{l,n}z))$$

Terhalle et al. Proc. SPIE **8192**, 81020V (2011)

Visible wavelength range: Boguslawski et al., Phys. Rev. A 84, 013832 (2011)

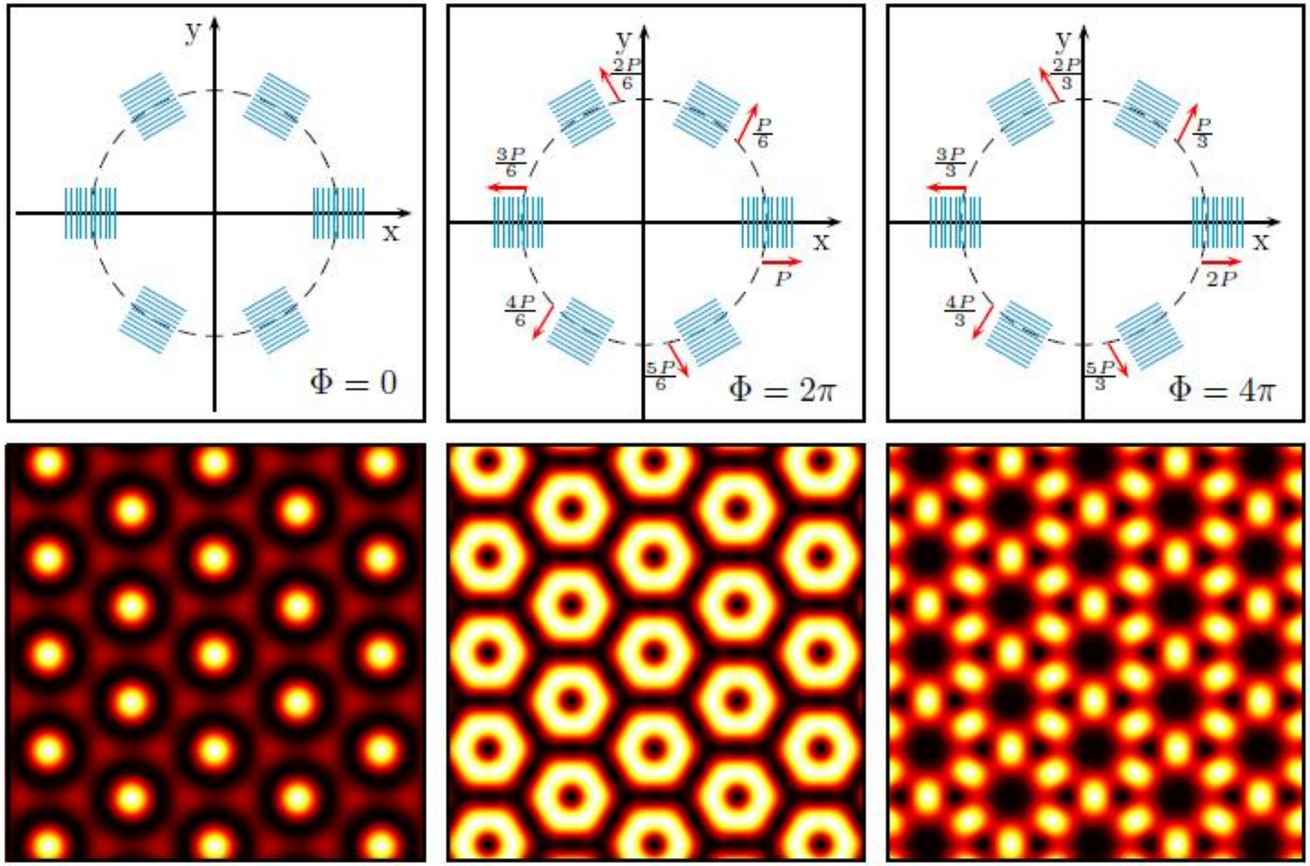
Phase-controlled EUV-IL: 4 beams

- 4-beam interference:



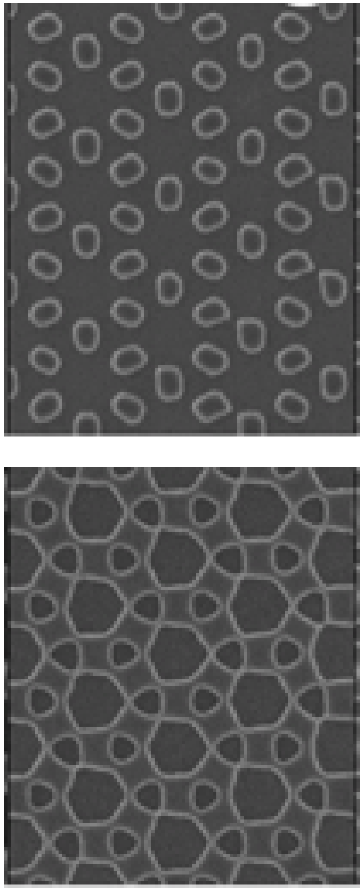
Phase-controlled EUV-IL: 6 beams

- 6-beam interference:



Hexagonal dots array | honeycomb | kagome

Kagome nanostructures

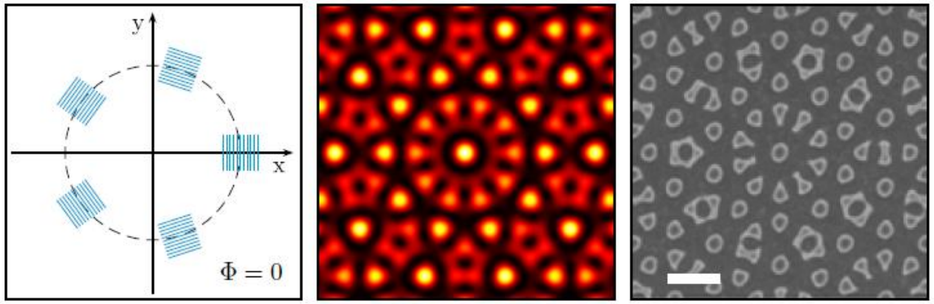


HSQ

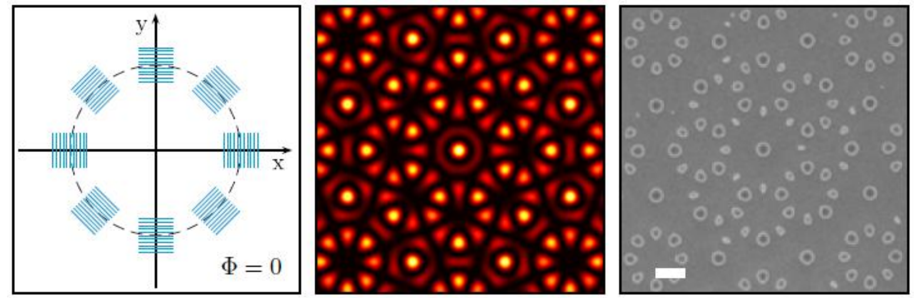
PMMA

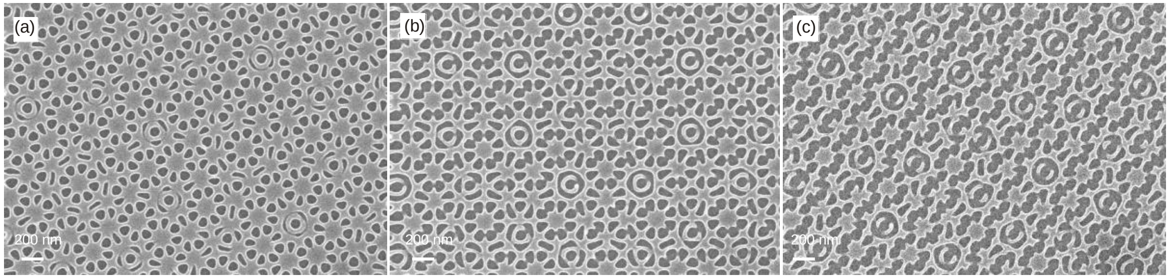
Quasicrystals (Penrose tilings)

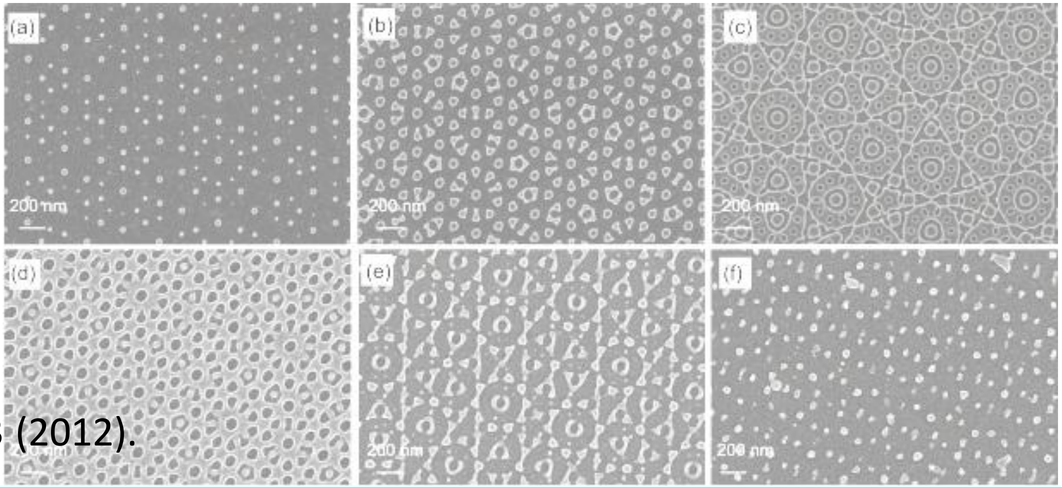
5-beam interference



8-beam interference:





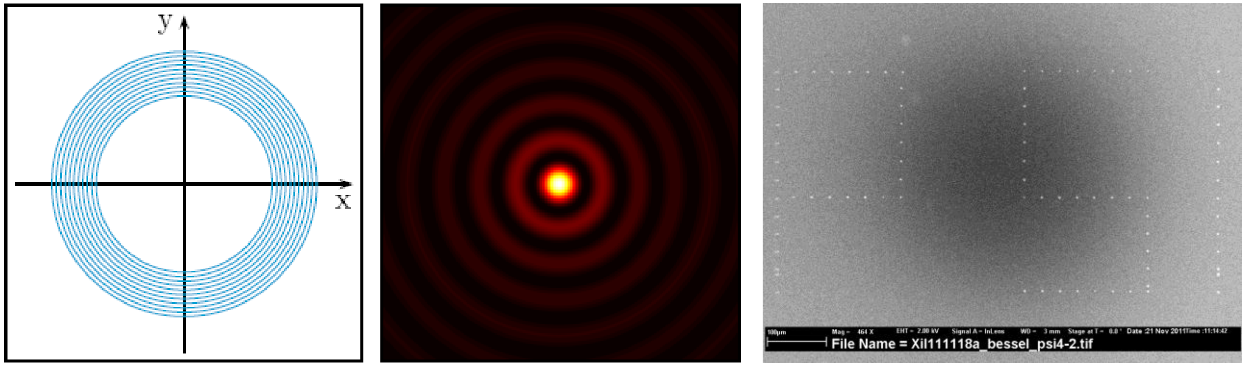


- Quasiperiodic patterns for photonics and alignment markers
- LIL is good but has low resolution
- E-beam is high resolution but pattern generation is difficult and only mimics the quasiperiodicity
- With EUV-IL; high resolution for alignment markes. high quality or shorter operation wavelength for photonics

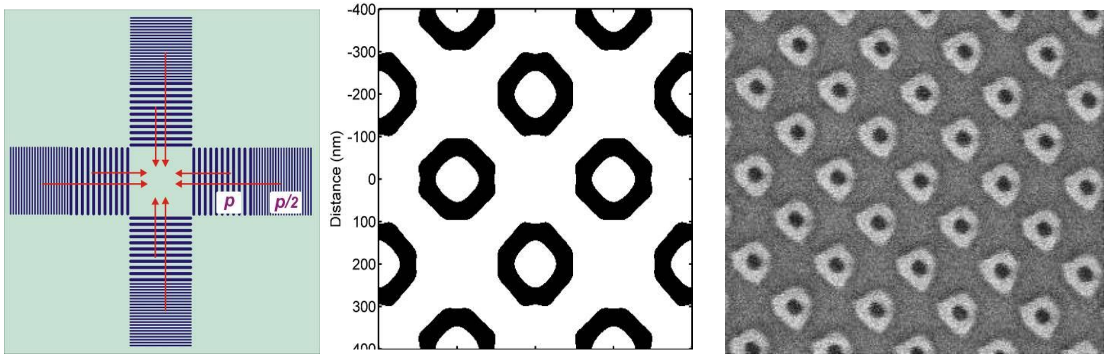
A. Langner et al., Nanotechnology **23**, 105303 (2012).

Other interference schemes

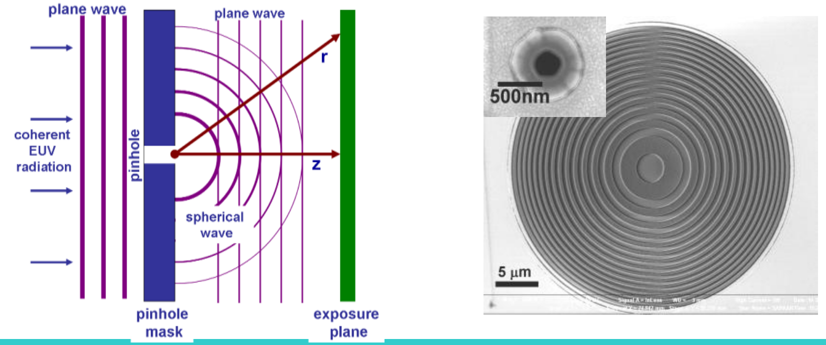
Non-diffracting EUV-Bessel beams:



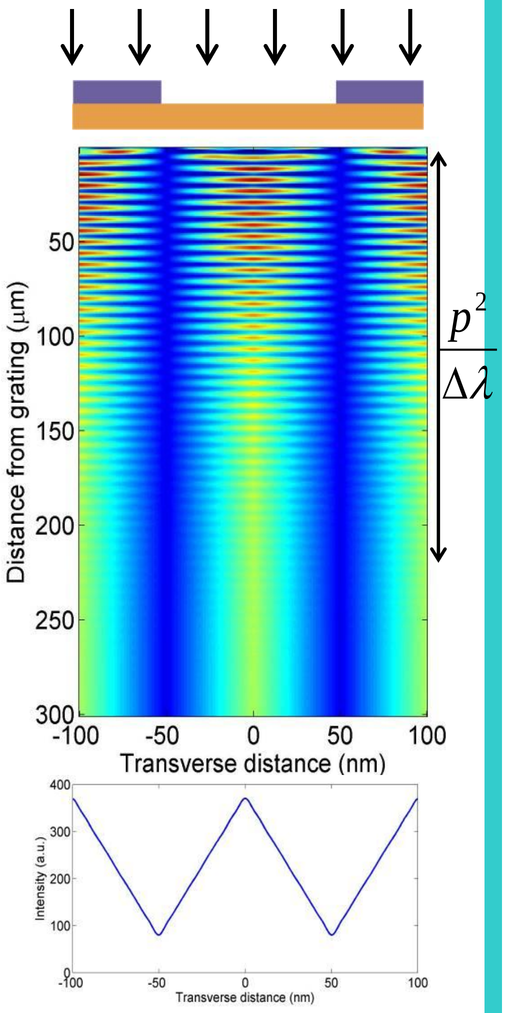
Incoherent multiple-beam lithography:



Holographic fabrication of Fresnel Zone plates

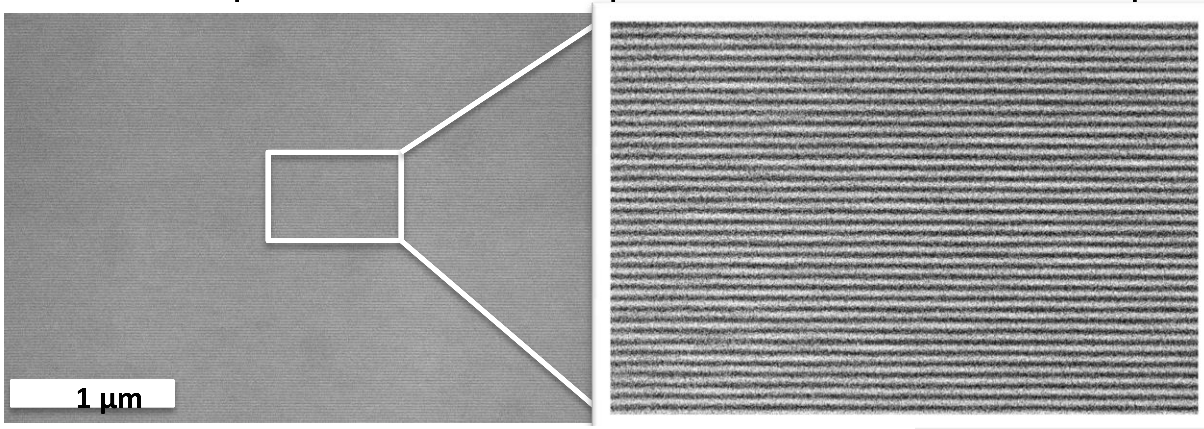


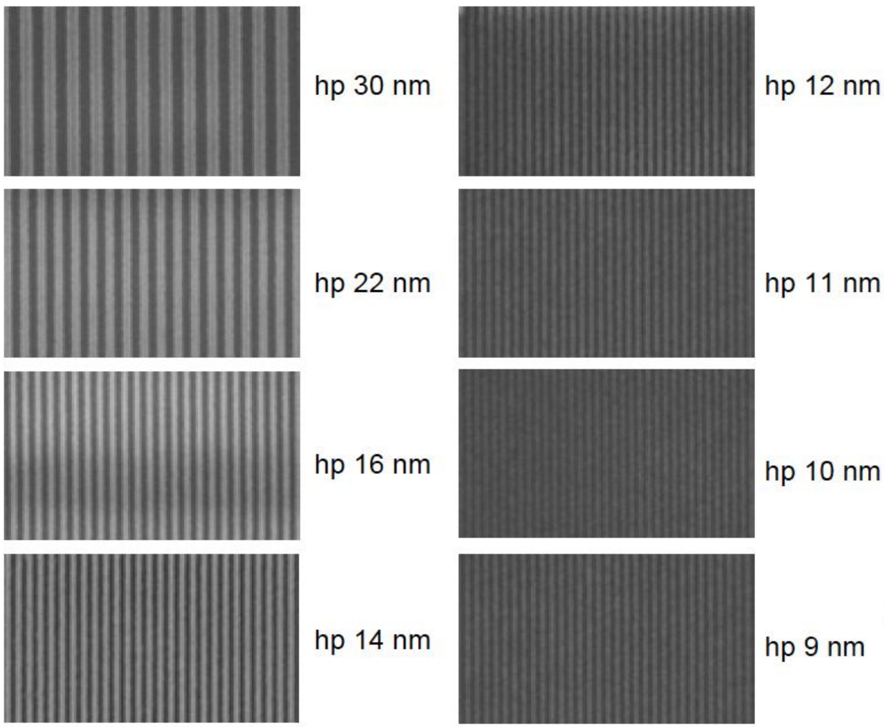
Achromatic Talbot Lithograph



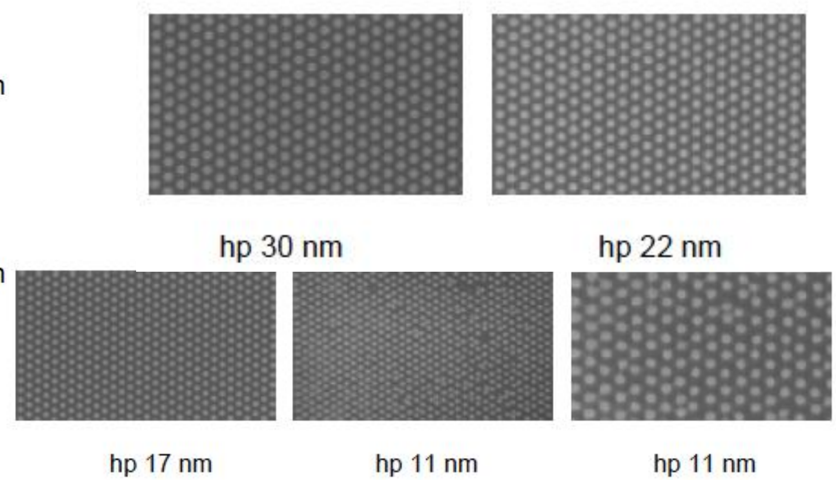
Record resolution in photon-based lithography

8 nm half-pitch: The smallest patterns ever written with photons!



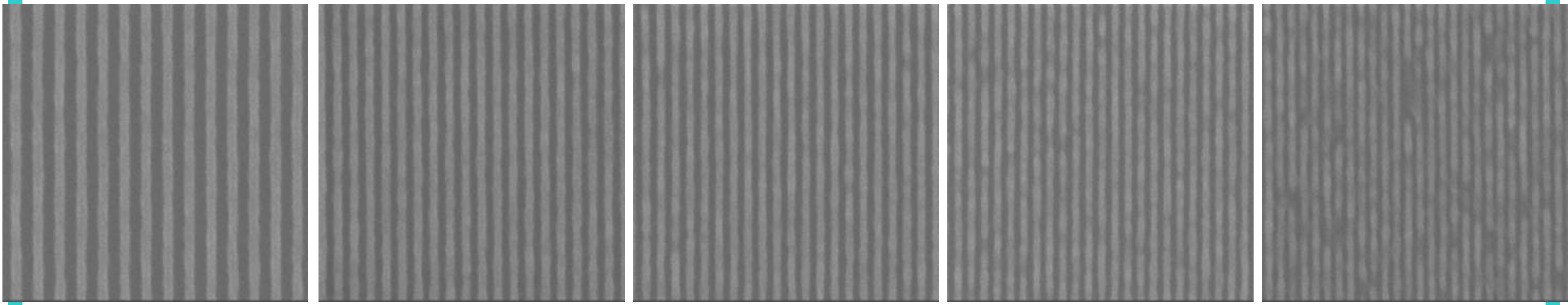


Both with Inpria and HSQ

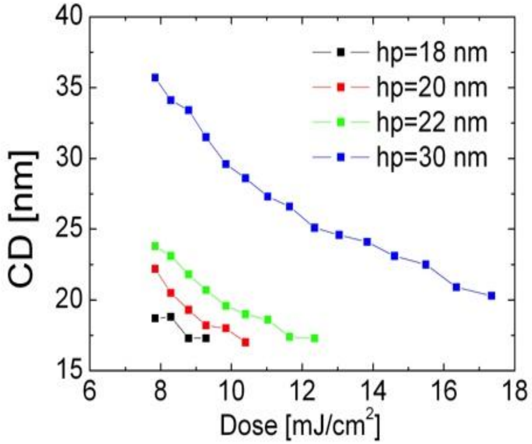


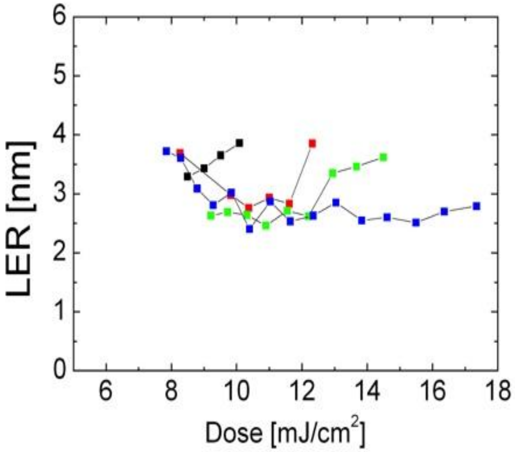
Evaluation with Resist-A

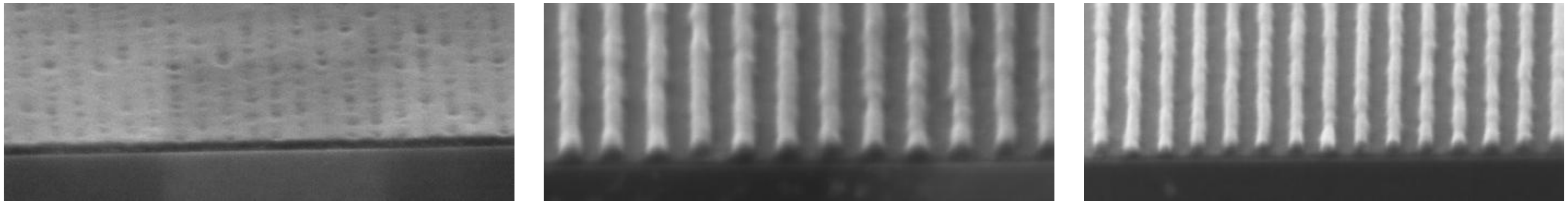
HP=30 nm **HP=22 nm** **HP=20 nm** **HP=18 nm** **HP=16 nm**



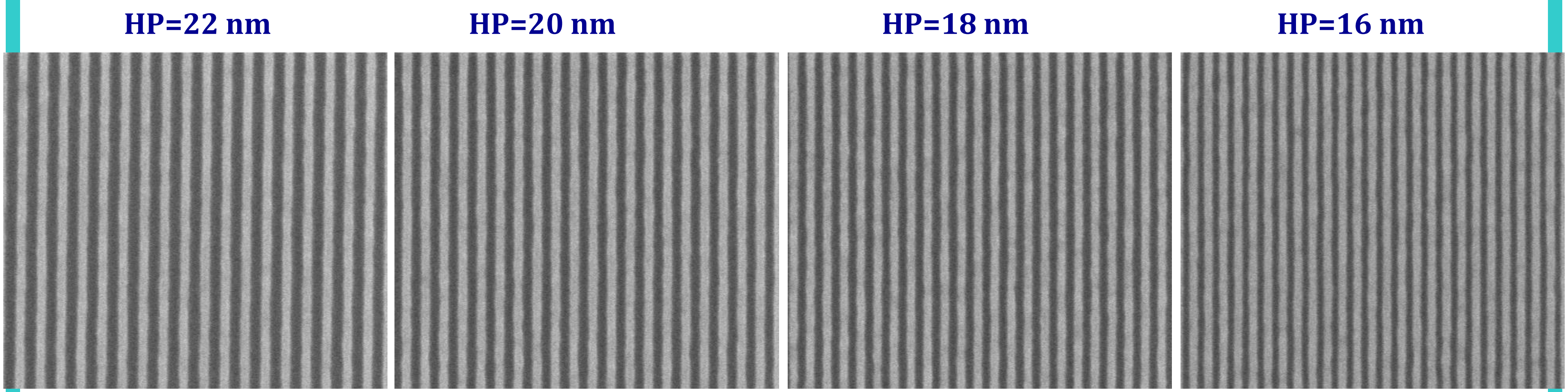
Thickness=35 nm
PAB: 105 ° C/ 90 s
PEB: 90 ° C/90 s
Dev: 2.38% TMAH/ 30s

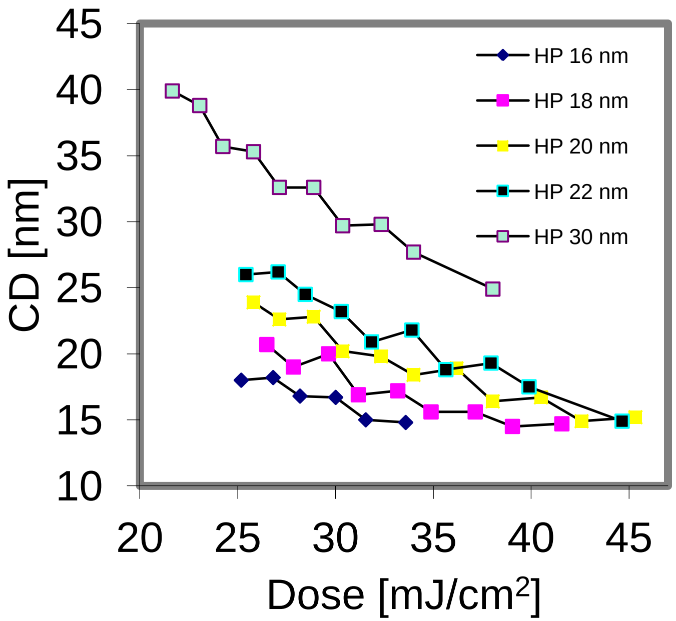


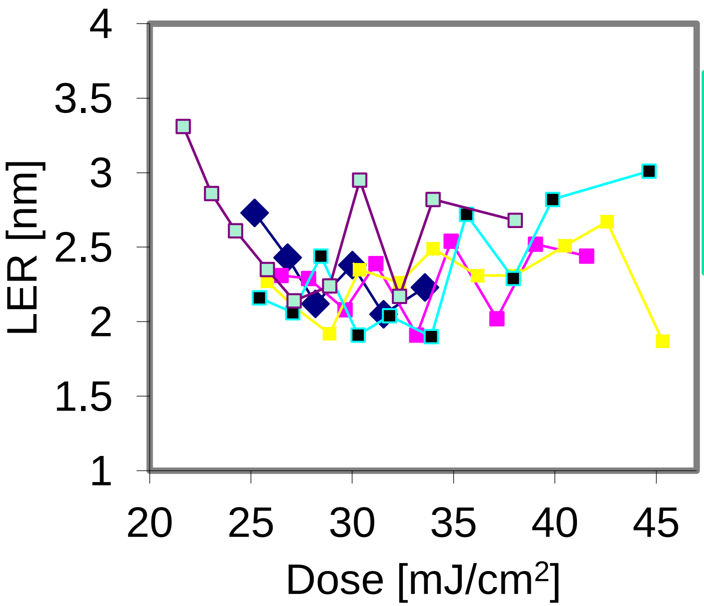




Resist-B

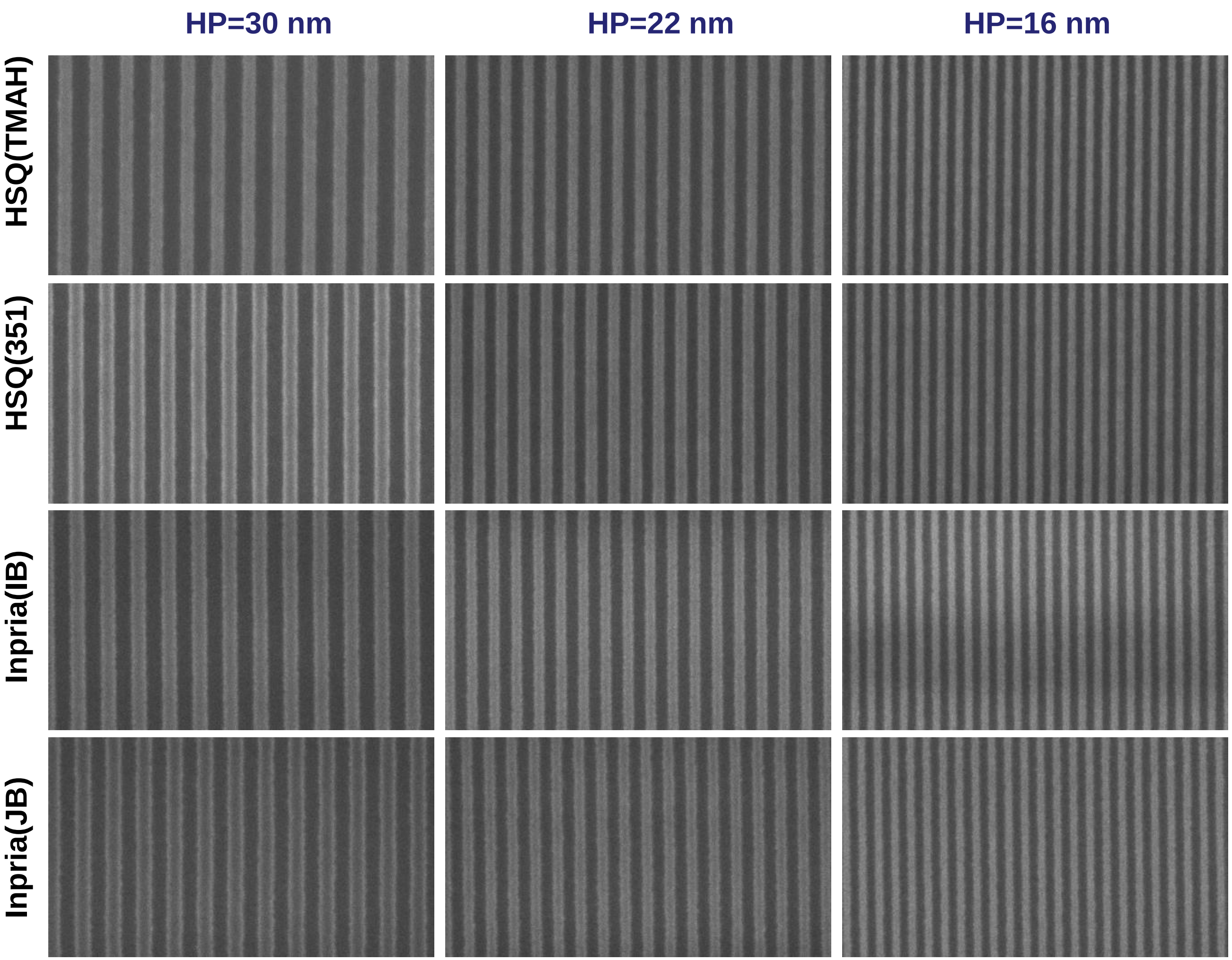


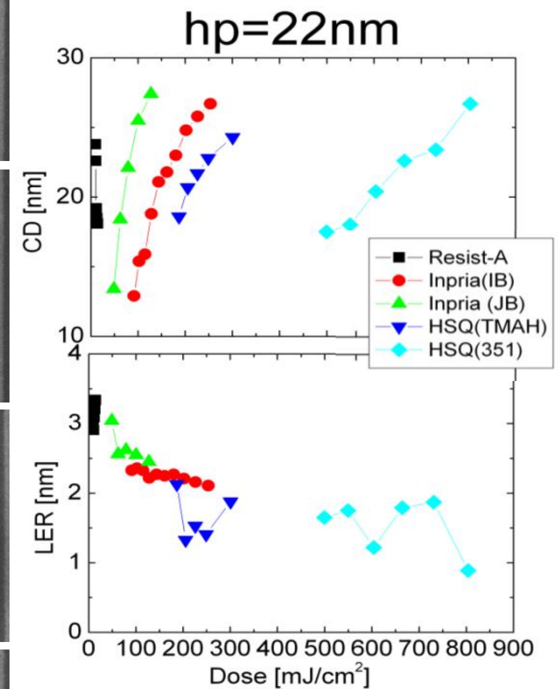




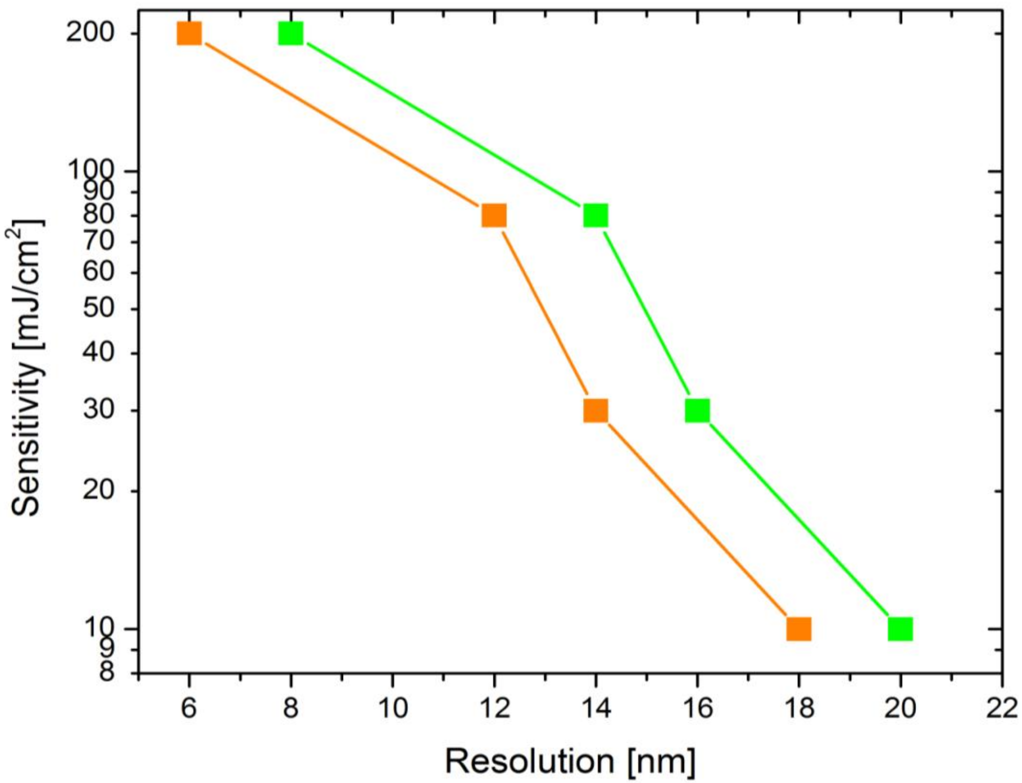
Thickness=30 nm
PAB: 130 ° C / 60 s
PEB: 100 ° C / 60 s
Dev: 2.38% TMAH/ 30s

Inorganic resists





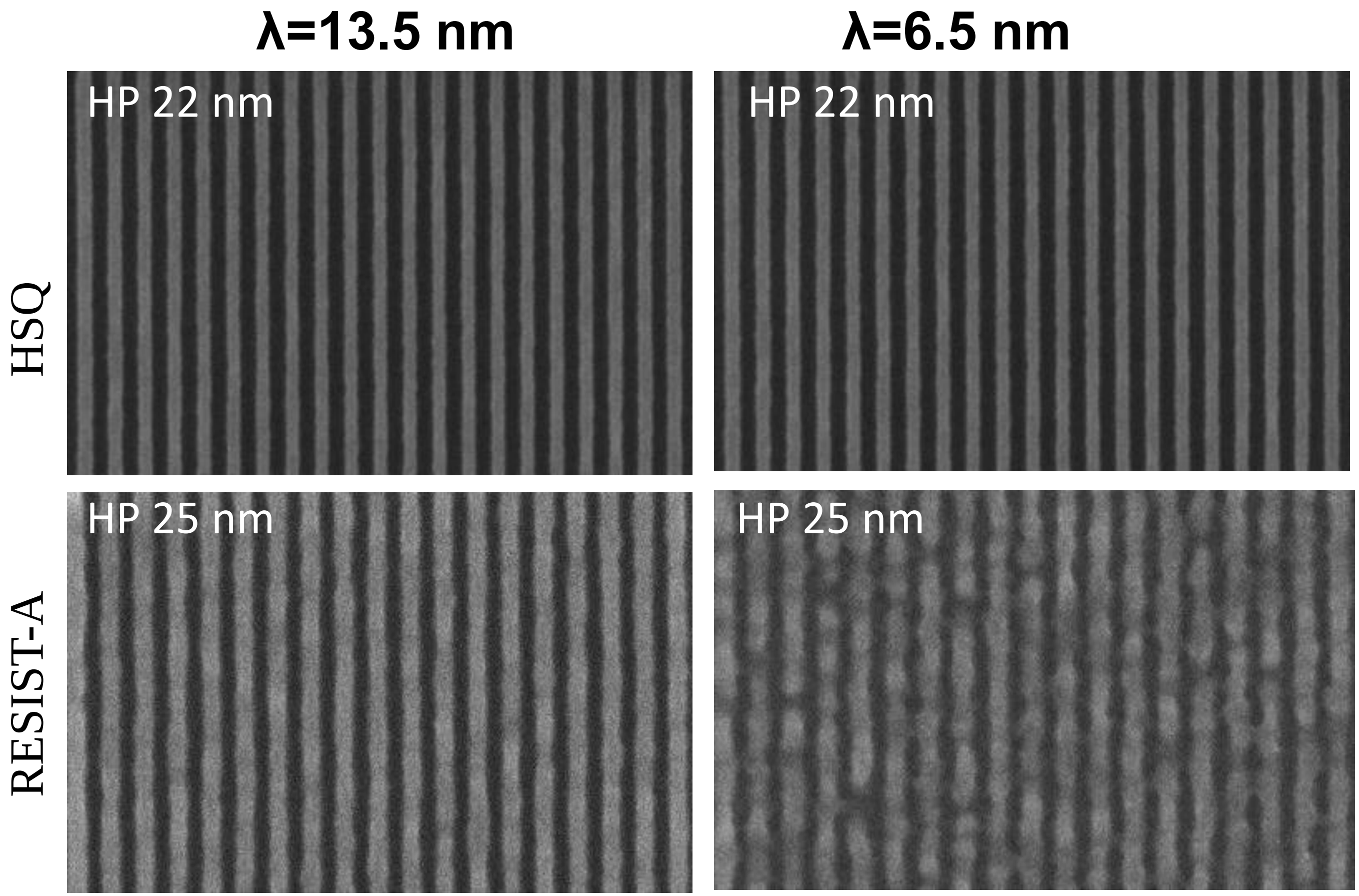
Status of EUV resists



- Demonstrated. For sub-16 nm sensitivity is assumed to be hp independent as for >16 nm
- Not clearly demonstrated. But has great potential, or requires process optimization for LER or pattern collapse.

Patterning with λ=6.5 nm

First patterning results with BEUV or deep EUV or hard EUV



Note: These results are preliminary and not conclusive yet.

Conclusions & Outlook

- EUV-IL is a powerful tool for academic research:
  - versatile nanostructures, high resolution, high throughput, large area.
  - It gets really exciting in sub-10 nm.
- EUV-IL is a powerful tool for resist evaluation for future technology nodes:
  - cost-effective, pitch-independent aerial image, High resolution
  - different wavelengths (BEUV).
- Current status of EUV resist development
  - Resist A: 18 nm hp resolution with ≈10 mJ/cm^2 sensitivity: LER improvements necessary (1) with thicker resist using pattern collapse mitigation and (2) line smoothing strategies
  - Resist B: 16 nm hp resolution with ≈30 mJ/cm^2 sensitivity
  - For 16 nm hp senstivity less than 30 mJ/cm^2 should be feasible
- With decreasing HP: pattern collapse becomes the limiting factor
- Going from EUV to BEUV: resist development is necessary..

Acknowledgments: We thank the resist suppliers: Inpria, Shin Etsu, and JSR. Thanks to Todd R. Younkin for discussions.

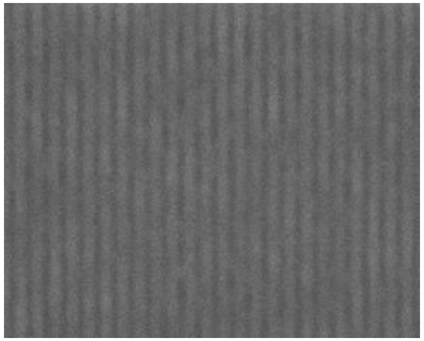
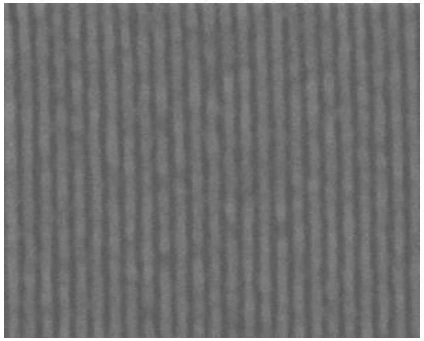
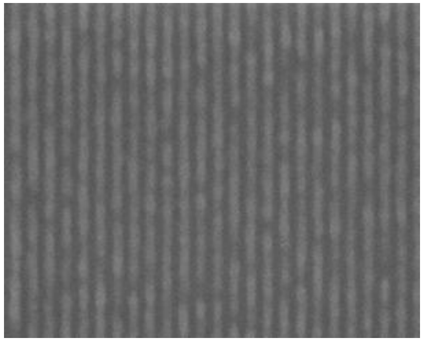
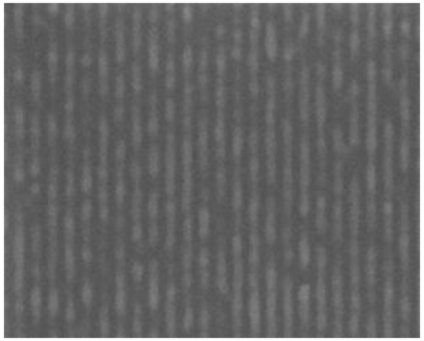
Thank you for your attention!

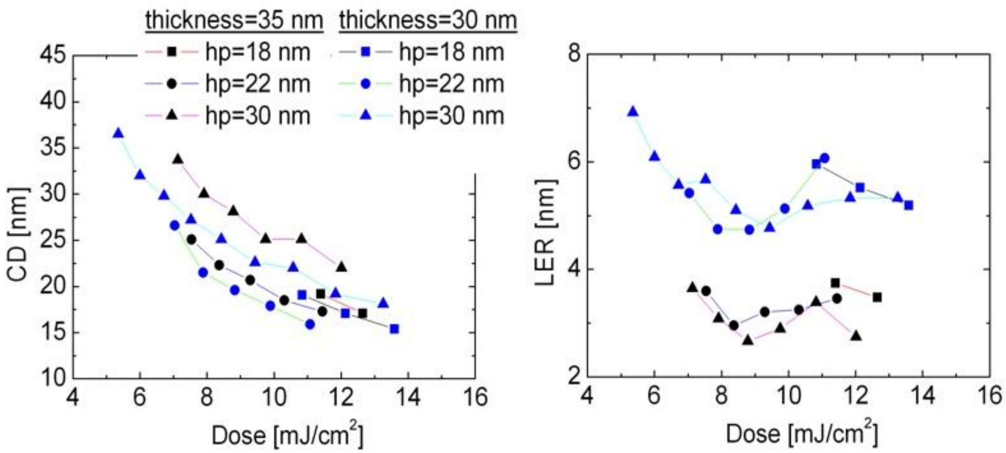
Resist comparison

Resist name	Substrate	PAB	Thickness	PEB	Developer /Time	Sensitivity @ hp 22 nm	Resolution
Resist-A	Si/Underlayer	105°C /90s	35 nm	90°C /90s	TMAH 0.26N /30s	**9.5 mJ/cm² ±1.1 mJ/cm²**	**18 nm**
Resist-B	Si/Underlayer	130°C /60s	30 nm	110°C /60s	TMAH 25% /30s	**30 mJ/cm²**	**<16 nm**
Inpria(X15JB)	Si/O_2 Plasma	80°C /120s	20 nm	80°C /120s	TMAH 25% /120s	**80 mJ/cm²**	**<16 nm**
Inpria(XE15IB)	Si/O_2 Plasma	80°C /180s	20 nm	80°C /60s	TMAH 25% /30s	**163 mJ/cm²**	**<<16nm**
HSQ(TMAH)	Si	No	35 nm	No	TMAH 2.6N /60 s	**229 mJ/cm²**	**<16 nm**
HSQ(351)	Si	No	35 nm	No	351 /30 s	**659 mJ/cm²**	**<<16 nm**

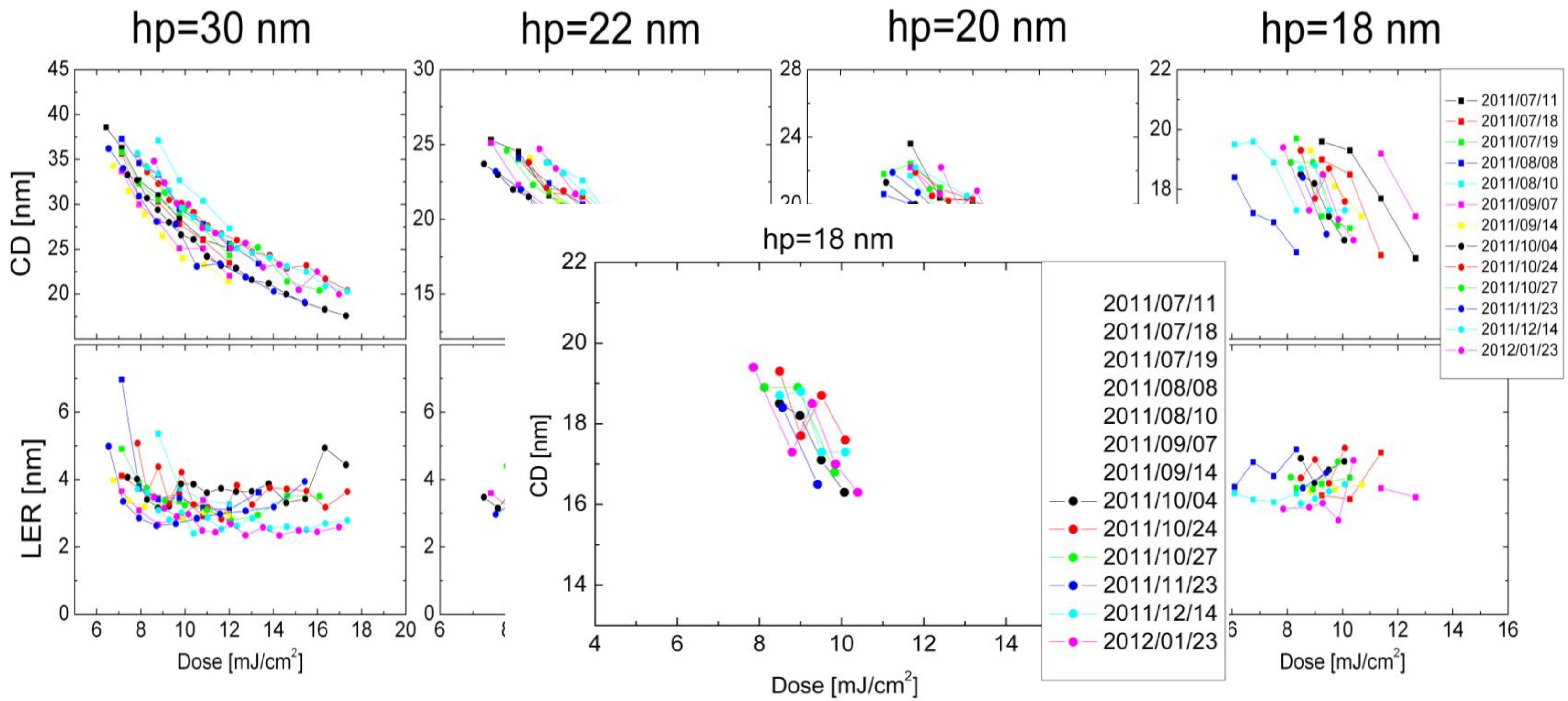
Resist-A: Thinner resist for 16 nm hp

HP=16 nm, through dose

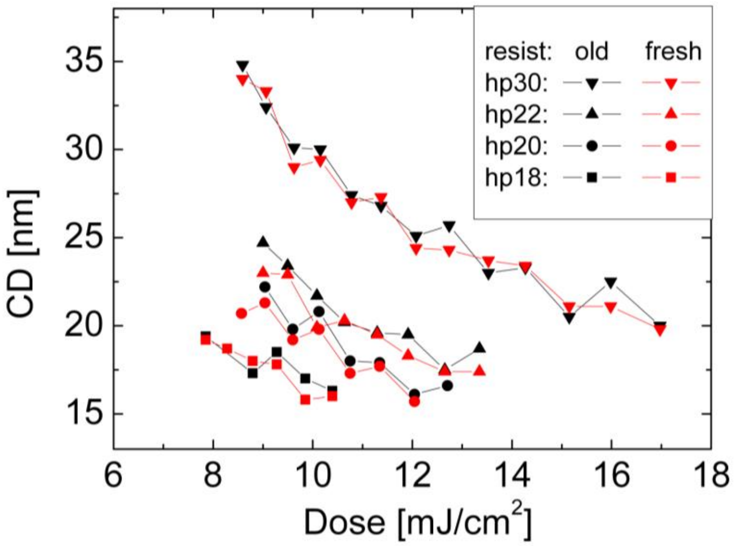







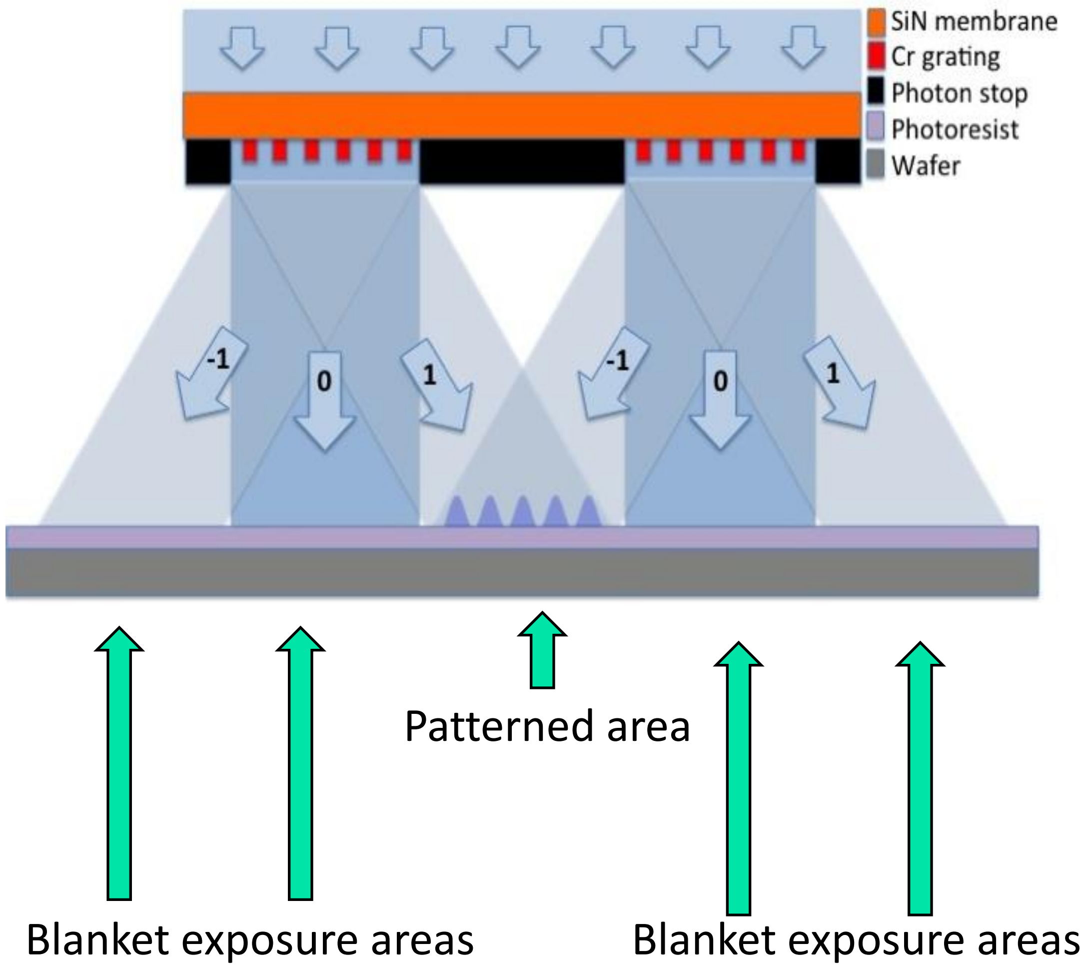
Reproducibility tests



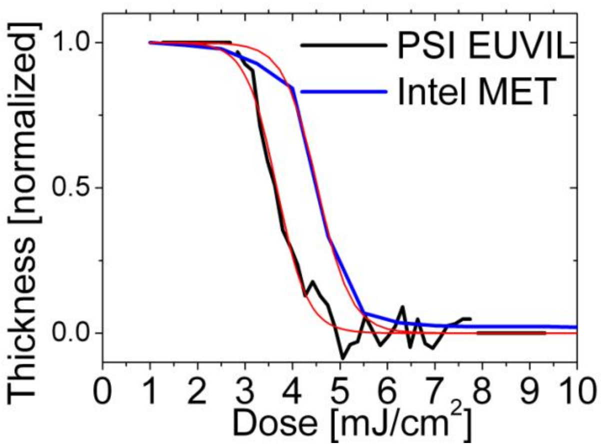
Resist-A: Shelf-life



Dose calibration



Dose to clear for Resist-A



Sub-10 nm patterning with 2. order diffraction