JARA|FIT

COST Action MP0601

EUV interference lithography with a laboratory gas discharge source

Next-generation nanopatterning

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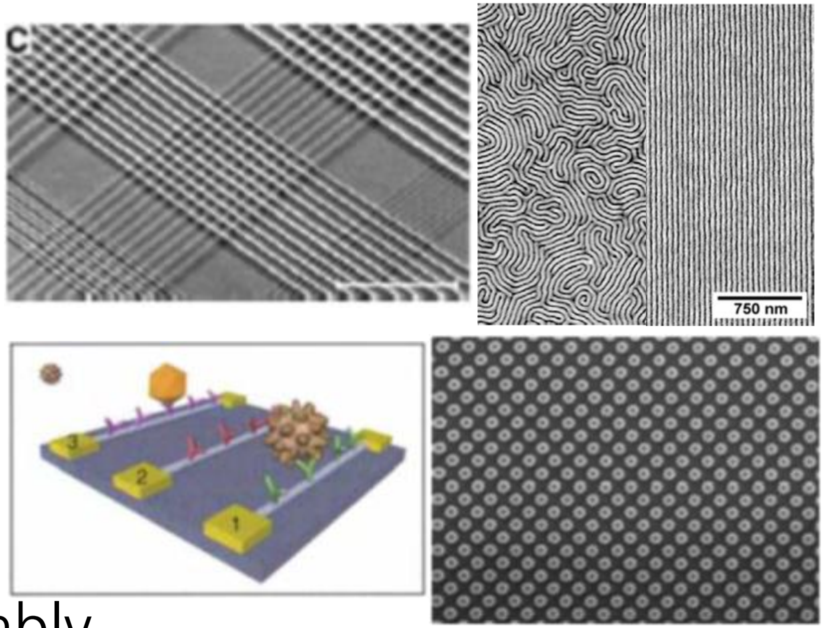
Outline

- Motivation
- Laboratory EUV sources
- Possible approaches to EUV-IL
- Optimisation of DPP EUV source
- Experimental realization
- Proof of principle exposures
- Summary and outlook

Motivation



There is a strong demand for lab-scale EUV IL setup for creation of dense periodic patterns with sub-20 nm resolution.

Applications:

- templates for guided self-assembly
- ultra high density patterned magnetic media
- nano-optics, meta-materials
- quantum dot 2D and 3D arrays, nanowire arrays

Nanopatterning Solutions

- Electron-beam Lithography: High resolution, limited throughput, charging effects, proximity effect
- Nanoimprint Lithography: High resolution, high throughput , low cost, one-to-one replication, master degradation, contact, residual layer
- Scanning probe Lithography: High resolution, limited throughput
- Self-assembly: High resolution, low pattern perfection
- EUV Interference Lithography: High resolution, moderate throughput, no charging effect, negligible proximity effect, periodic patterns only

Currently EUV-IL is synchrotron-based ➡ limited availability

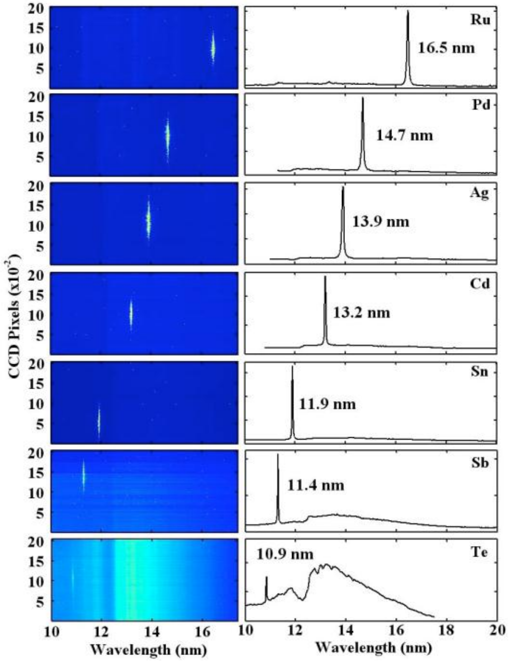
Relevant lengths for EUV-IL

	Length	Significance
Wavelength	~10-15 nm	Spatial resolution of aerial image
Absorption length	~50-100 nm	Exposable film thickness, surface sensitivity
Photo/secondary electron path length	< 1-2 nm	Blur, proximity effect
Average distance between photo-absorption events	~2.5nm (for dose 1000J/cm^3, E_{ph}=92.5eV)	Statistics, roughness
Recording medium/process	?	Molecular size, diffusion, dissolution

H. Solak, MNE07, Copenhagen, 26 Sep 07

Laboratory EUV sources - Coherent

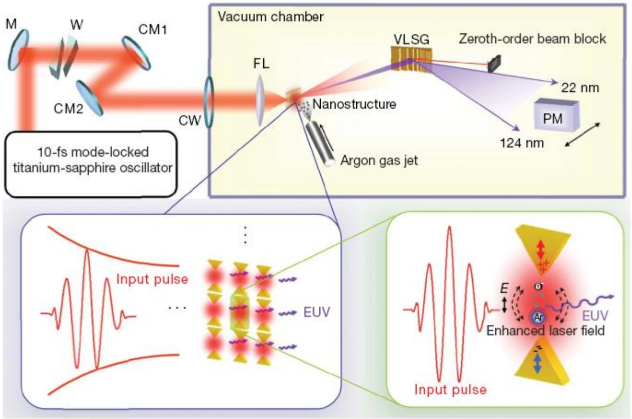
Direct lasing



P~1 μW

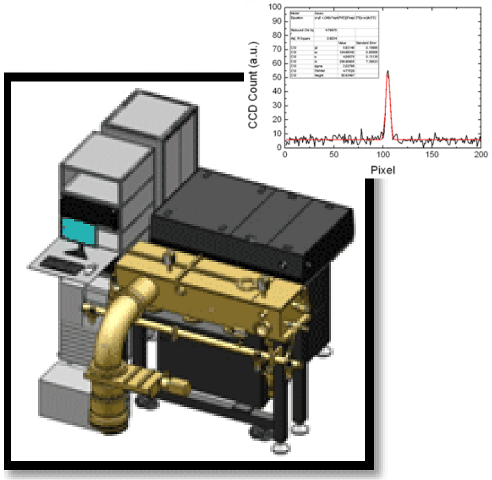
*J. Rocca, Colorado State University

High-order harmonic generation in an atomic gas ionized by a fs laser pulse.



P~ 1 nW

*S.Kim et al, Nature 453,757 (2008)

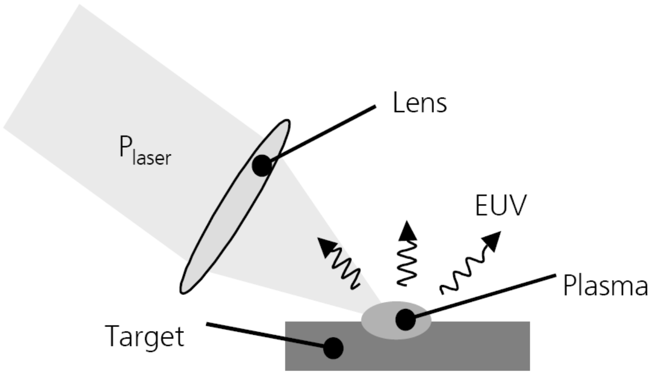


P= 48 nW

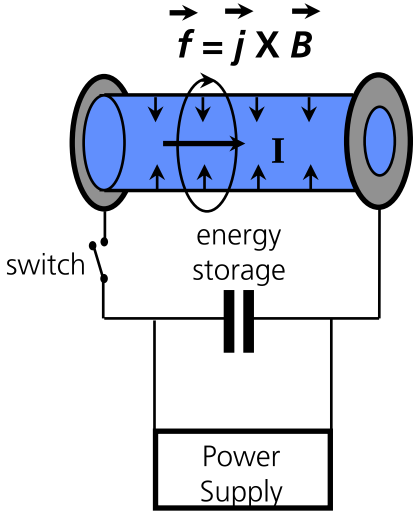
*FST Co. & Samsung (2011)

Laboratory EUV sources – Not coherent

Laser produced plasma sources (LPP)



Discharge plasma sources (DPP)

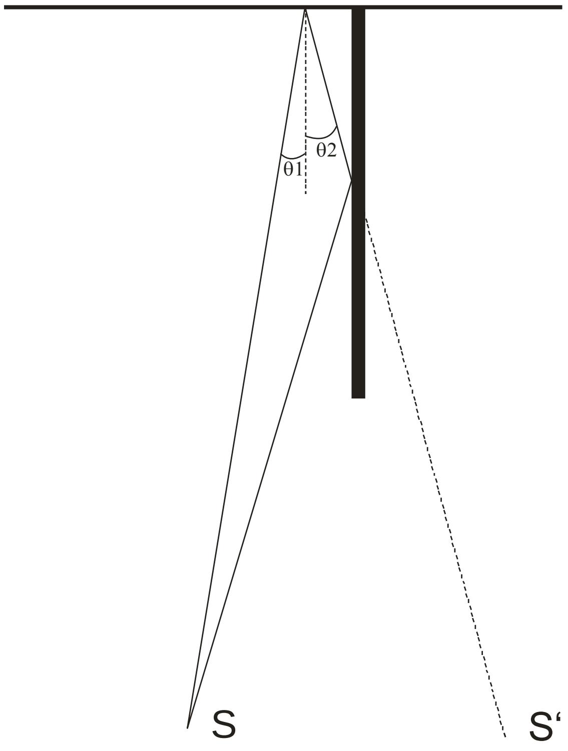


Power is high enough, but spatial and temporal coherences are low.

Interference schemes with relaxed coherence requirements have to be used.

Possible schemes for EUV-IL

Lloyd mirror



Resolution is limited by $\lambda/(\sin\theta_1+\sin\theta_2)$, max $\lambda/2$.

No mask needed.

Requirements		
Temporal coherence	Spatial coherence	Other
High	High	High mirror quality

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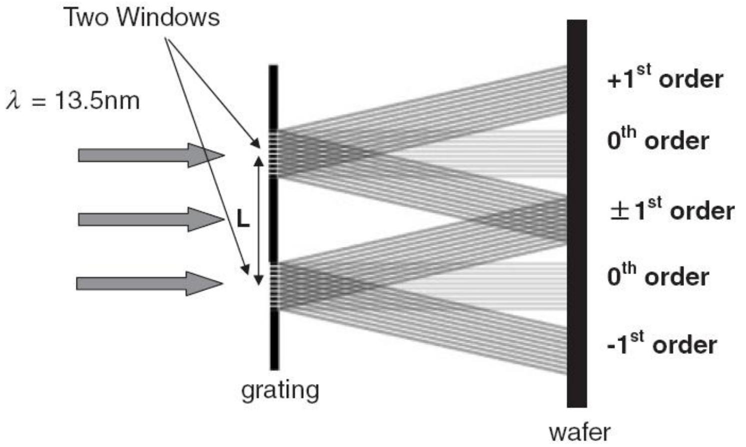
Paris, November 18th, 2011

Possible schemes for EUV-IL

Grating

Classical synchrotron scheme

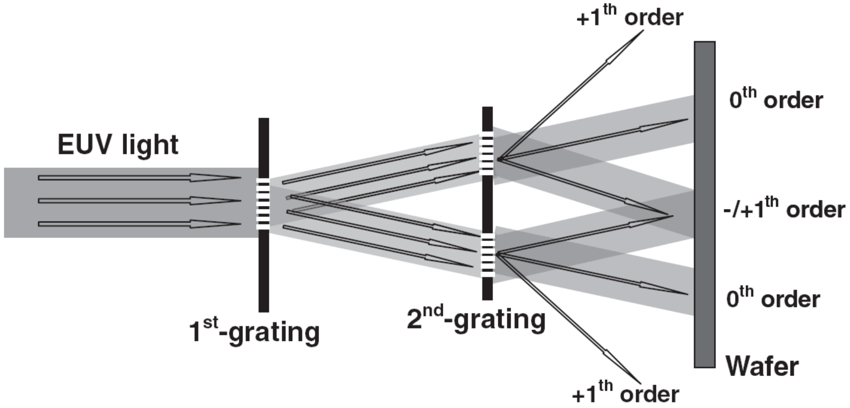


Will not work with thermal sources due to high spatial coherence requirements

Requirements	
Temporal coherence	Spatial coherence
Low	High (>L)

Possible schemes for EUV-IL

Double grating



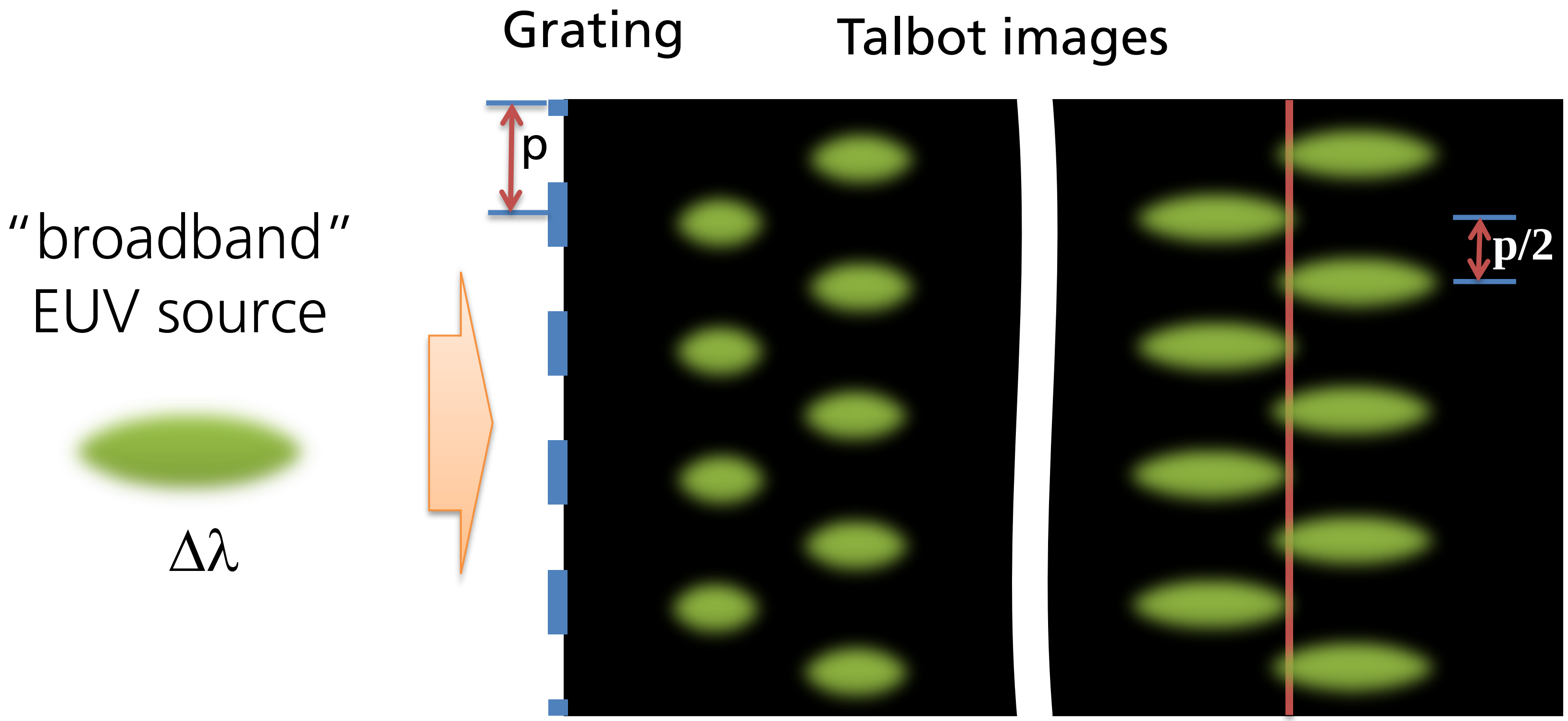
Additional grating provides solves the coherence problem… at the cost of ~90% of power

$$p = \frac{1}{2}\left[\left(\frac{1}{p_2}\right) - \left(\frac{1}{p_1}\right)\right]^{-1}$$

Resolution limit is $p_2/2$

Requirements	
Temporal coherence	Spatial coherence
Low	Low

Possible schemes for EUV-IL - Talbot



$$L_{Talbot} = \frac{2p^2}{\lambda}$$

Achromatic Talbot effect

*N.Guerineau (2000), H.Solak (2005)

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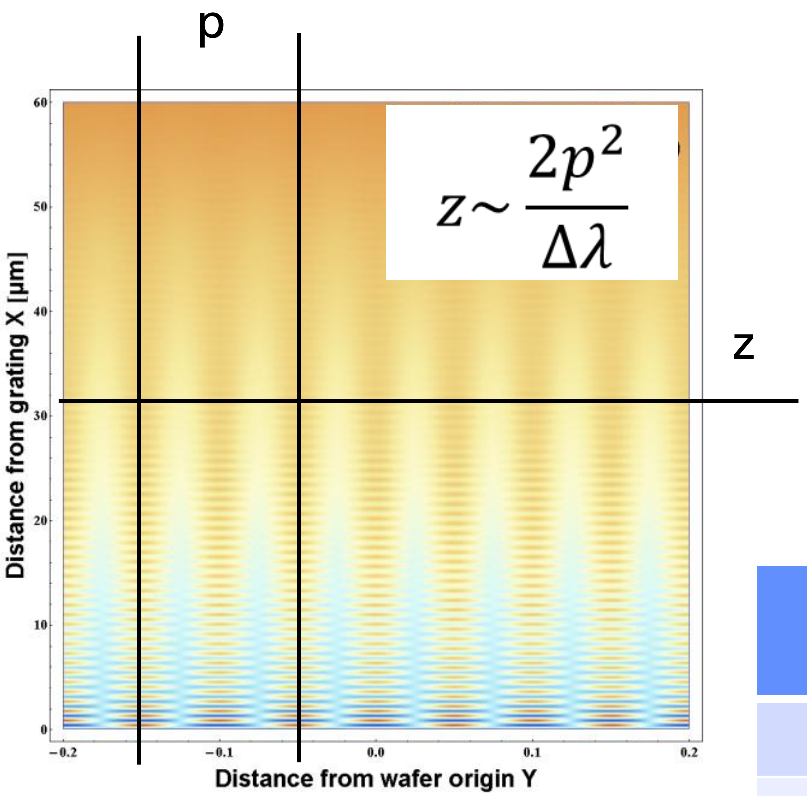
Talbot self-imaging



$$z \sim \frac{2p^2}{\Delta\lambda}$$

Requirements	
Bandwidth	Spatial coherence
$\Delta\lambda$~2-4%	$> 4p\frac{\lambda}{\Delta\lambda}$

Mask period	Bandwidth @11nm	Required coherence
100 nm	3.2 %	12.5 μm
40 nm	3.2 %	5 μm

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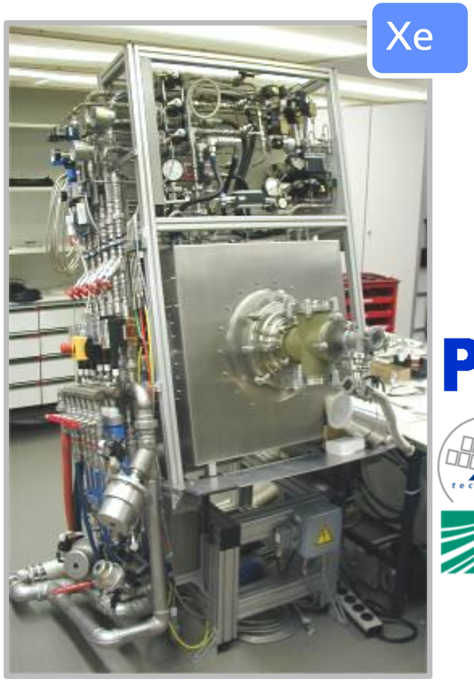
DPP EUV source

Repetition rate up to 4 kHz

EUV (10 – 20 nm): > 400 W/2πsr

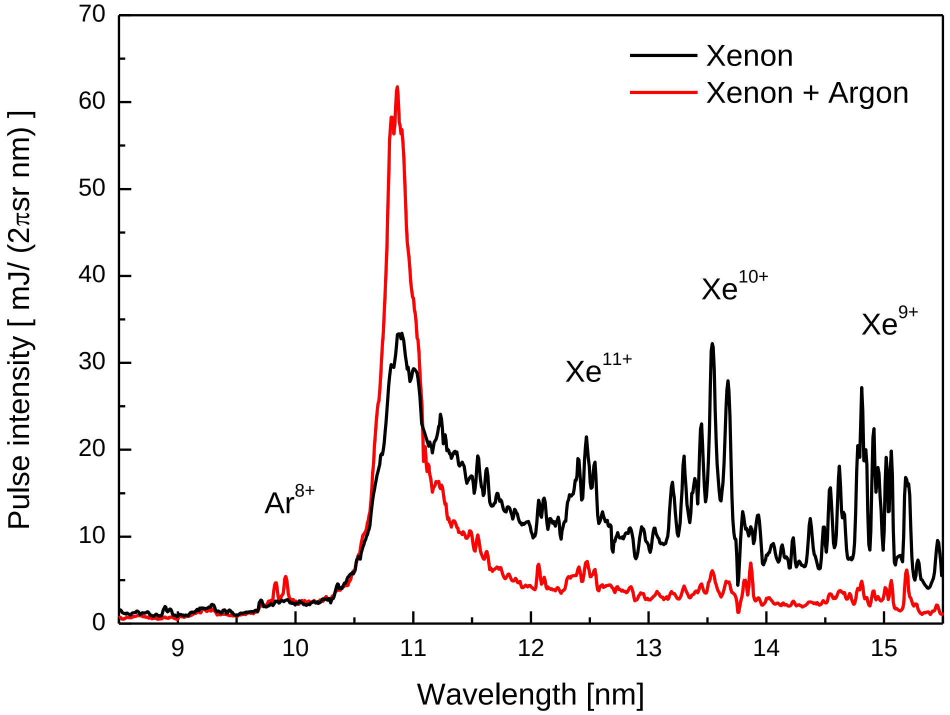
EUV (13.5 nm, 2% bw): 65 W/2πsr



PHILIPS

XTREME technologies

Fraunhofer ILT



Admixture of Ar to Xe plasma allows to supress 12-16 nm lines resulting in radiation at 10.9 nm with 3.2% bw

K. Bergmann, S.V. Danylyuk, L. Juschkin, J. Appl. Phys. V.106, 073309 (2009)

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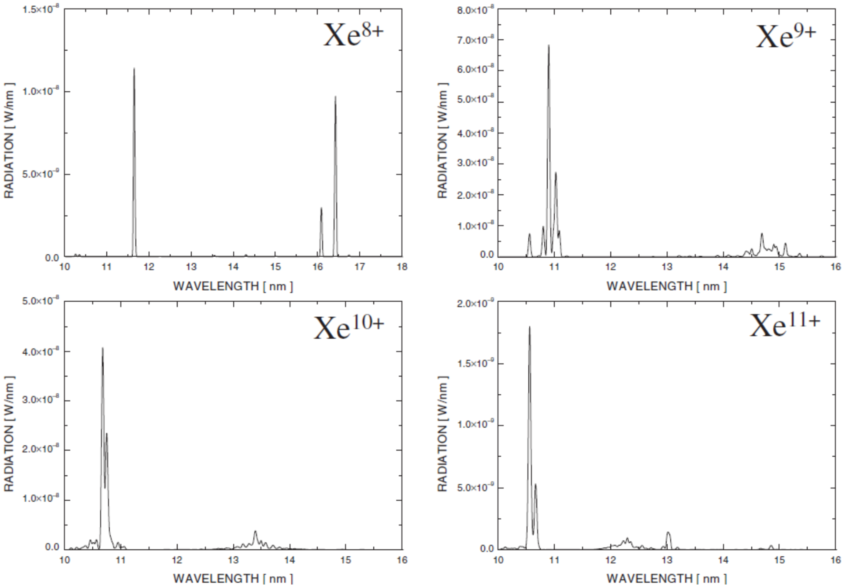
Source optimisation - Theory



11 nm - *4f-4d* transitions
Transition probabilities:
A_{ul}=5∗10^{11} s^{-1} to 2∗10^{12} s^{-1}

12 – 16 nm – *5p-4d* lines
Transition probabilities:
A_{ul}=5∗10^{9} s^{-1} and 5∗10^{10} s^{-1}

Brightness is scaling as:

$$\boxed{L \propto n_i^l n_e}$$

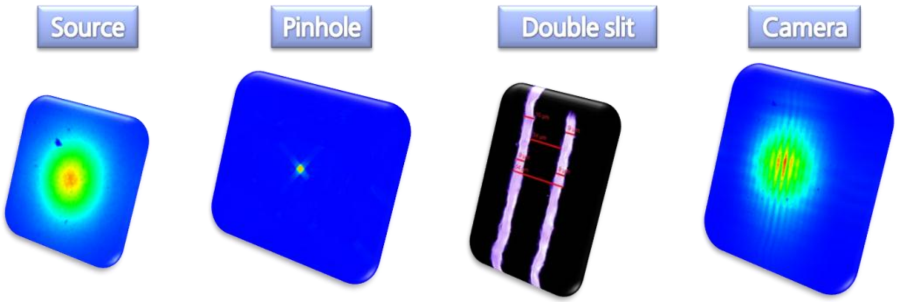
$$\boxed{L \propto \frac{\Delta\lambda_{Doppler}}{\lambda^5} \frac{1}{\exp\left(\Delta E / T_e\right) - 1}}$$

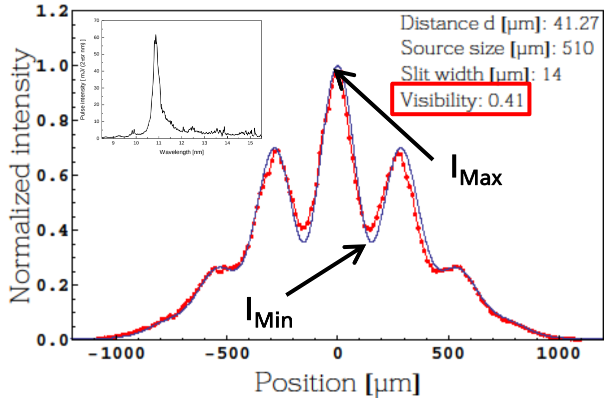
Optical depth, s, $\frac{1}{s} = \frac{\lambda^4}{8\pi c} A_{ul} \frac{g_u}{g_l} \frac{n_i^l}{\Delta\lambda_{Doppler}}$

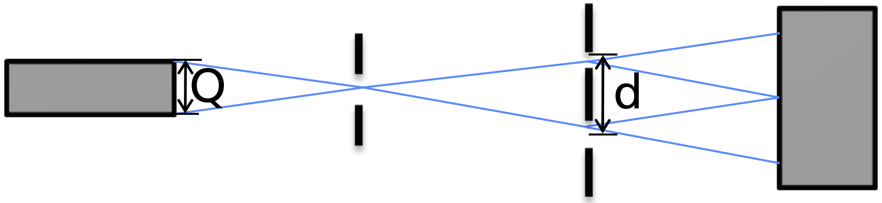
0.1 – 1 mm for *5p-4d* lines – optically thin
2 – 20 μm for *4f-4d* lines – optically thick

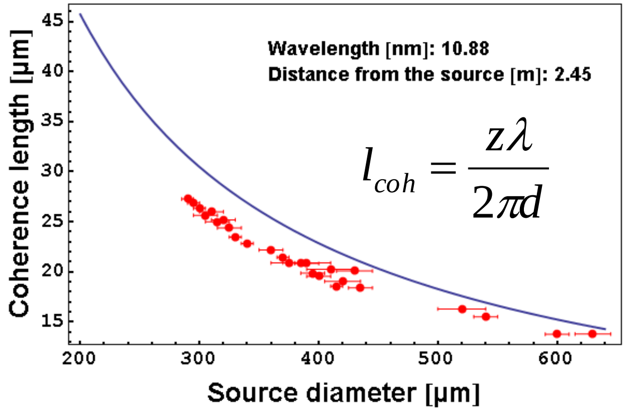
Reduction of the density of the emitting ions should not affect 4f-4d transitions strongly, if a constant electron temperature is maintained

Spatial coherence measurements









$$l_{coh} = \frac{z\lambda}{2\pi d}$$

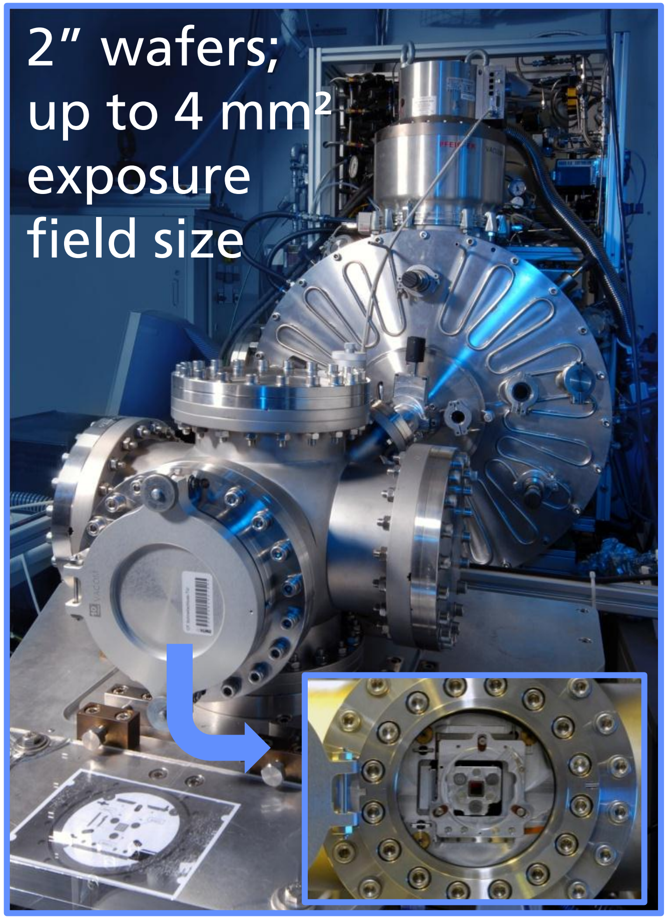
$$V = \frac{I_{Max}(d,Q) - I_{Min}(d,Q)}{I_{Max}(d,Q) + I_{Min}(d,Q)} = |\mu|$$

V : Visibility

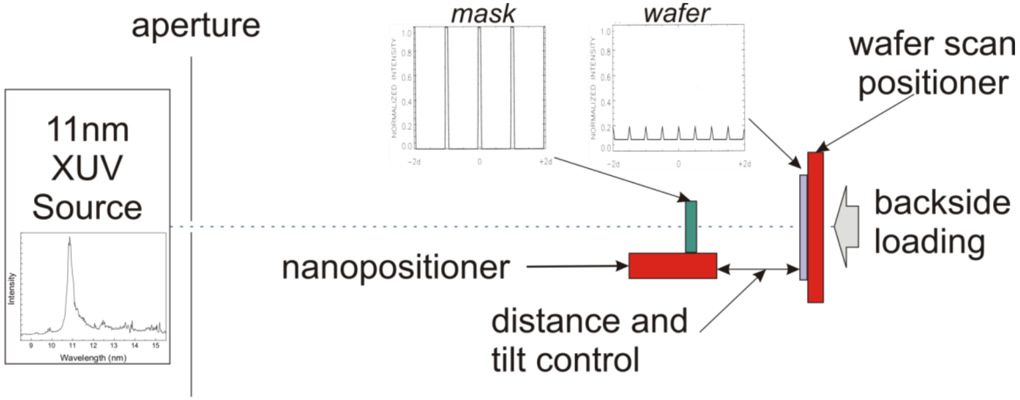
μ : Degree of Coherence

Spatial coherence lengths up to <u>27 µm</u> was measured

Exposure stage



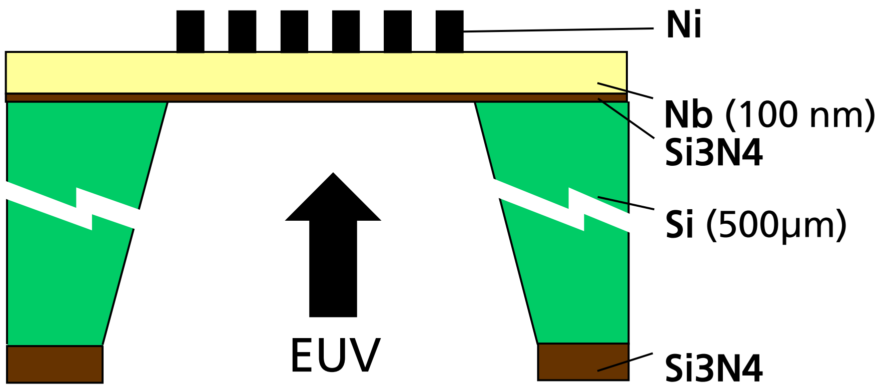
2" wafers;
up to 4 mm² exposure field size

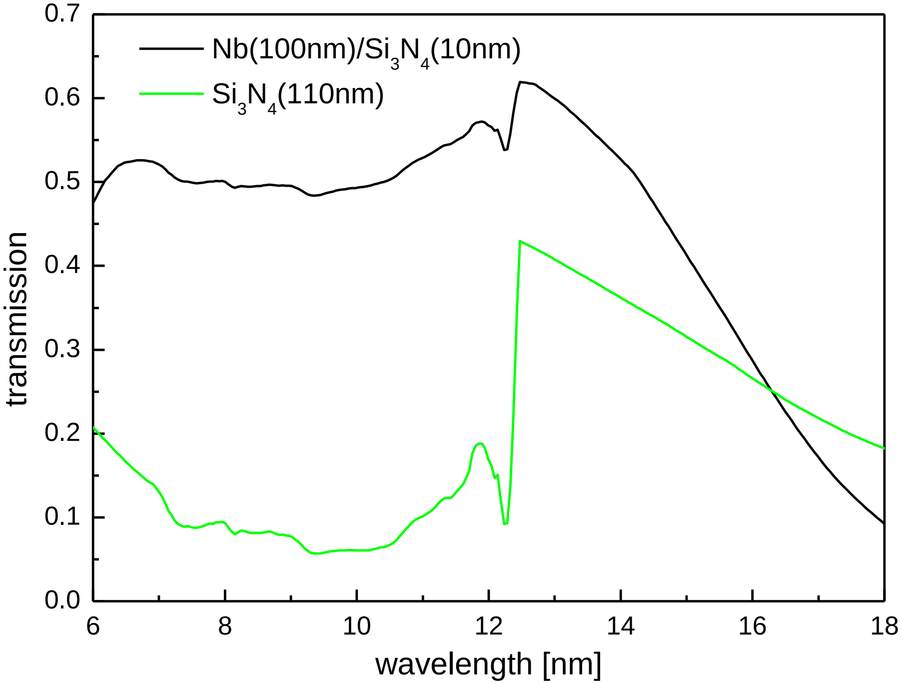


- Wafer-mask control with nanometer precision
- Compact and rigid to minimize vibrations
- Minimum optical components to reduce power loss

Transmission masks

For wavelengths < 12.4nm conventional Si_3N_4-based technology is no longer efficient due to high silicon absorption





- Flat Nb membranes with size up to 4 mm^2 are achieved
- Resist patterned with 50 keV e-beam lithography
- Pattern transferred to ~80 nm thick nickel by ion beam etching
- EUV 1st order diffraction efficiency ~9-9.5%

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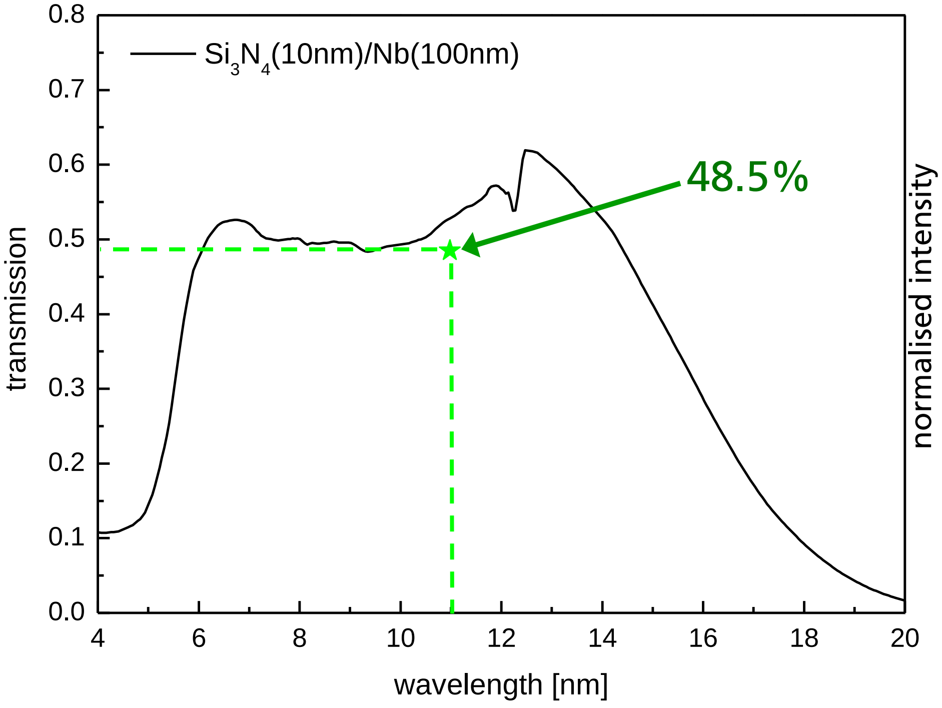
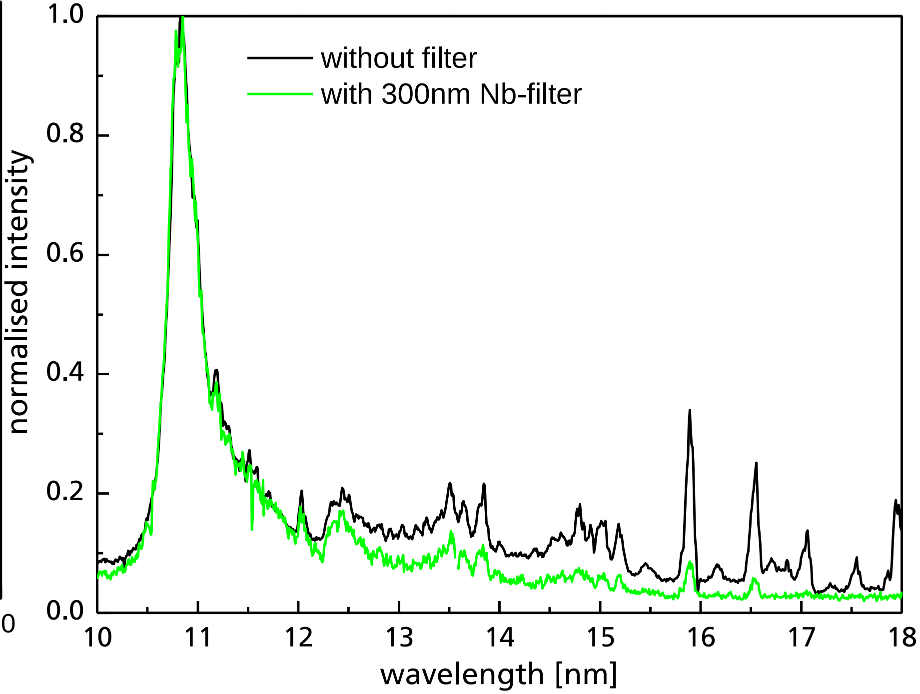
Transmisson measurements

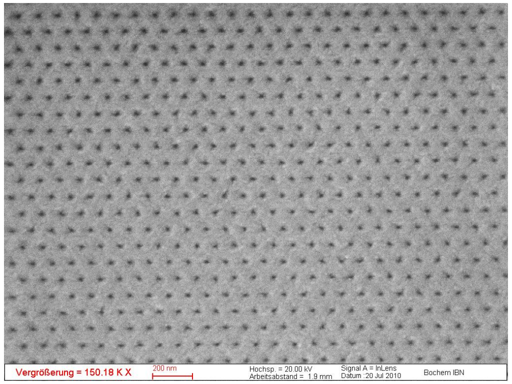




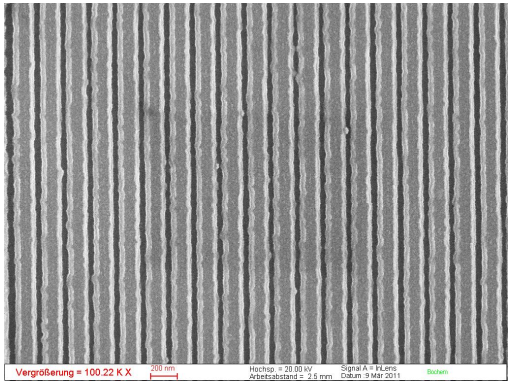
Theoretical transmission curves of the investigated membrane and measured transmittance at 11nm

Emission spectrum of DPP source with Xe/Ar gas mixture measured with and without 300nm Nb-filter

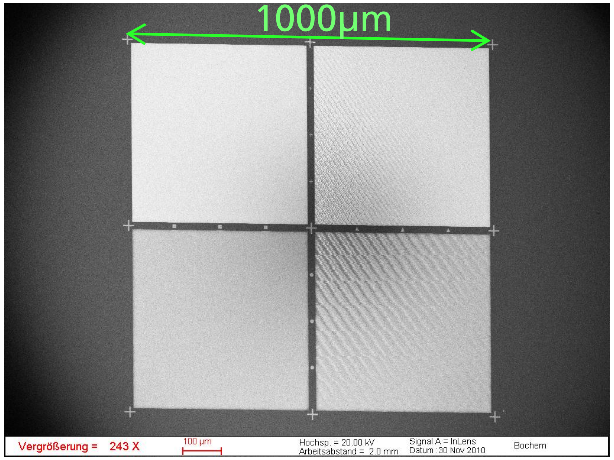
Mask Patterns



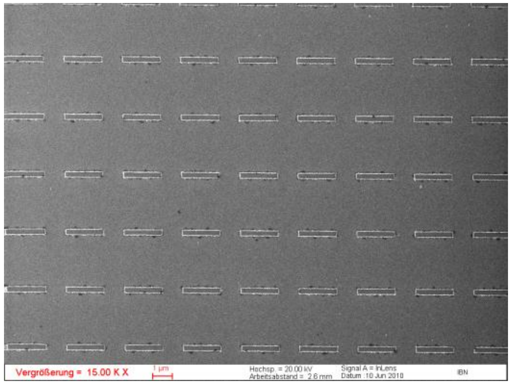
hex. pinhole array: p=100nm, dia.=40nm; scale=200nm



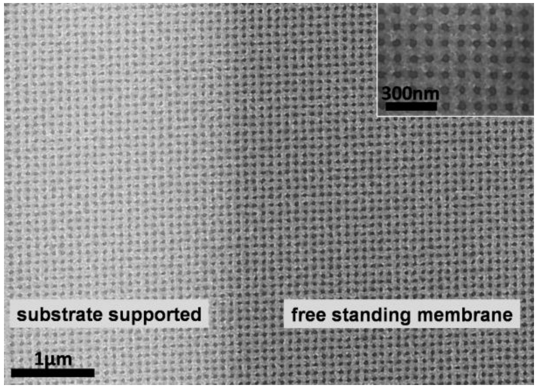
L/S array: p=200nm, lines=160nm, spaces=40nm; scale=200nm



mask layout incl. markers; scale=100µm



nanoantenna array: p=3µm, a=2µm, b=220nm; scale=1µm



rect. pinhole array: p=100nm, dia.=40nm

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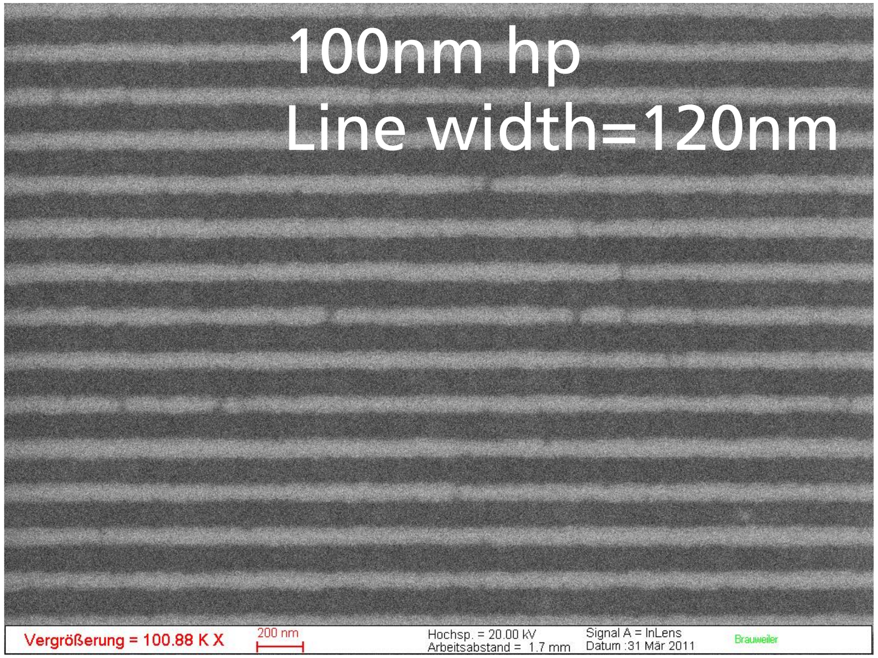
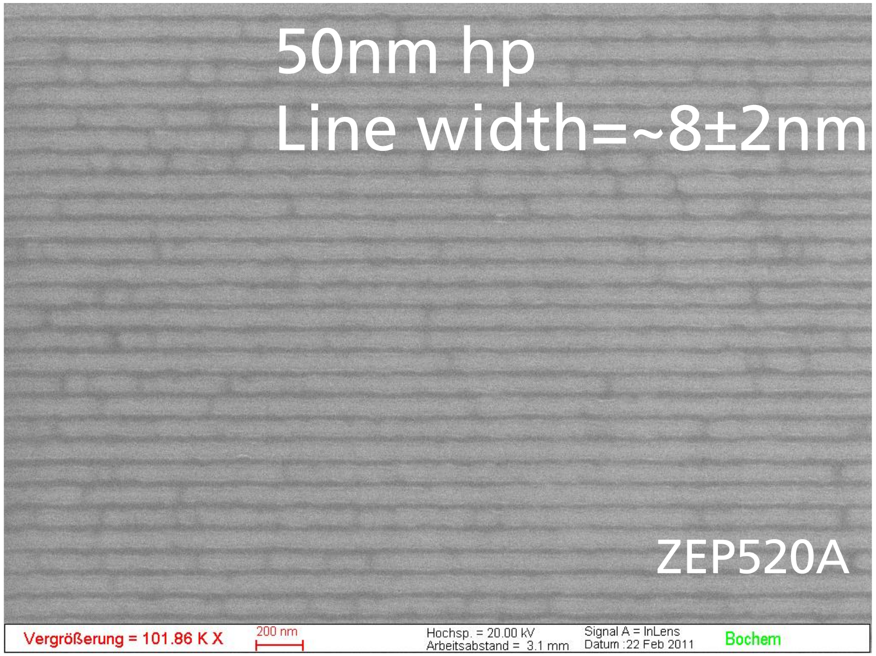
Test exposures – Talbot lithography



Distance to mask z few µm

Proximity printing



Distance to mask z= 50 µm
achromatic Talbot (with the
same transmission mask!)

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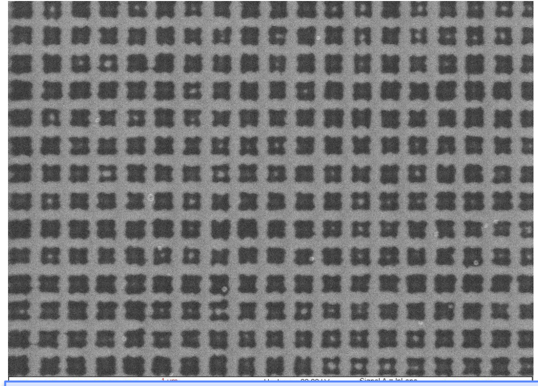
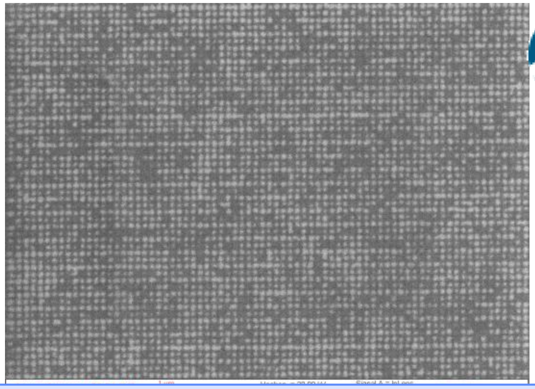
Applications



SFB 917
Nanoswitches

cross-bar arrays for PCRAM



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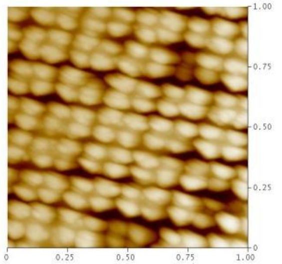
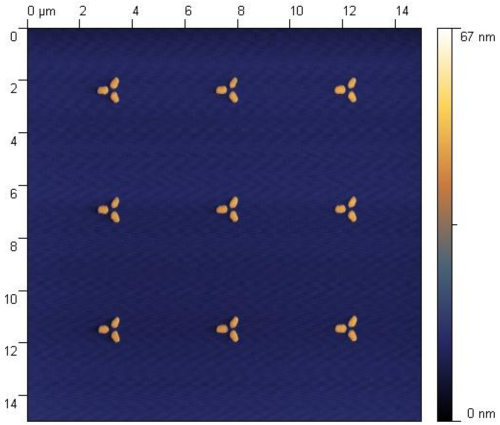
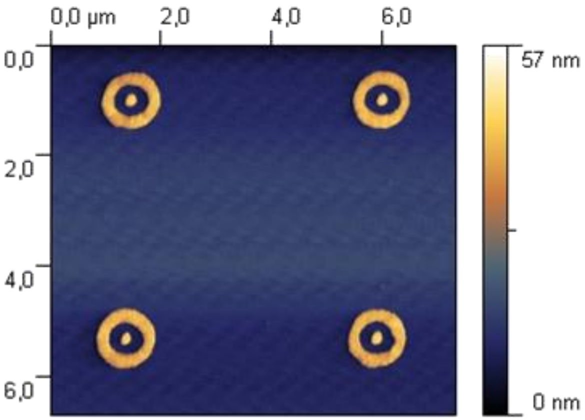
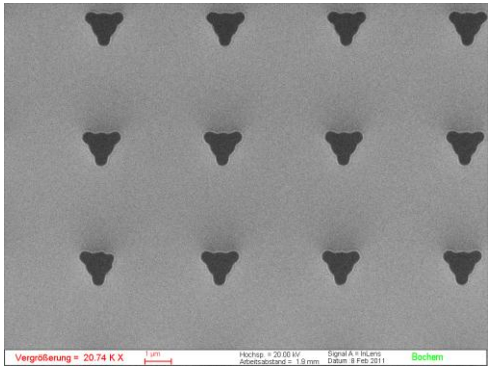
FORSCHUNGSZENTRUM



nanodot-arrays for QD self assembly

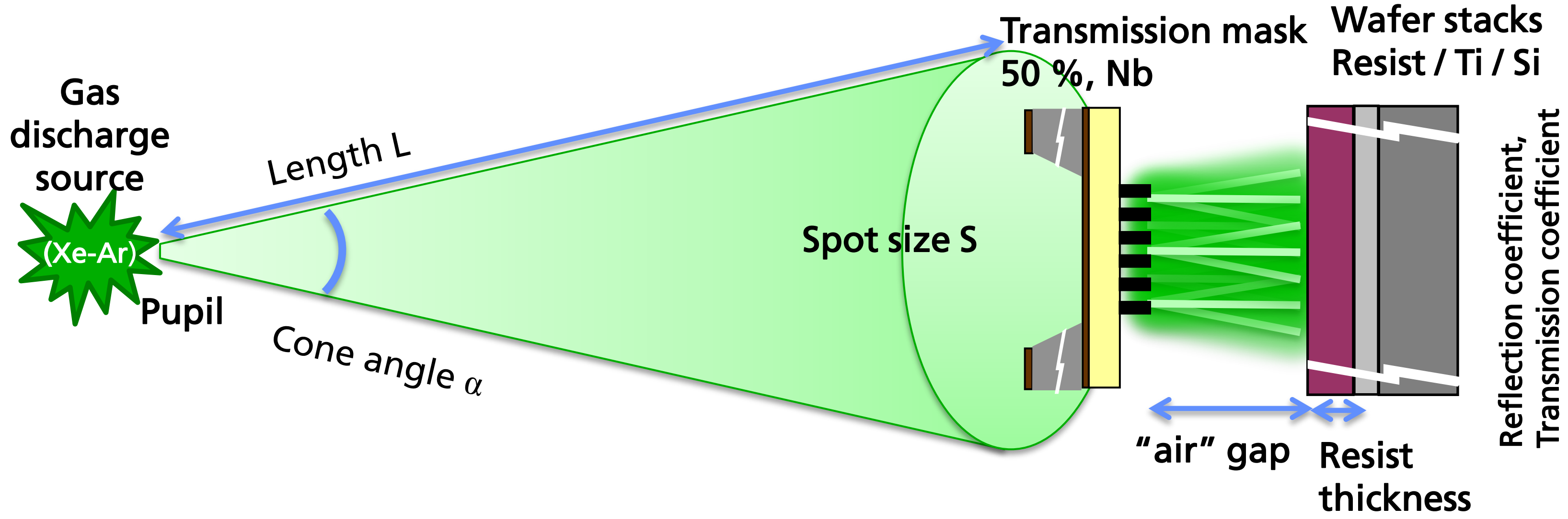






Nanophotonic resonators

Lithography simulations (Dr. Litho)



❖ Simulation modules (→ Research area)

Source
- ✓ Wavelength
- ✓ Bandwidth
- ✓ Pupil shape
- ✓ Cone angle
- ✓ Polarization

Mask
- ✓ Absorber
- ✓ Transmittance
- ✓ Scalar diffraction models (Kirchhoff, RS I, II)
- ✓ Rigorous diffraction simulation

Resist
- ✓ Stack, Resist parameter (Dill ABC)
- ✓ Exposure time
- ✓ PEB time, temp. (Diffusion)
- ✓ Develop time (Mack parameter)
- ✓ Resist profile (Process windows)

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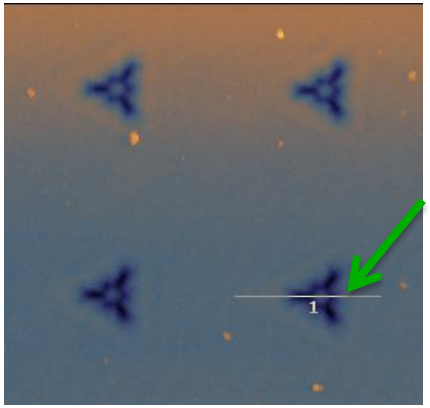
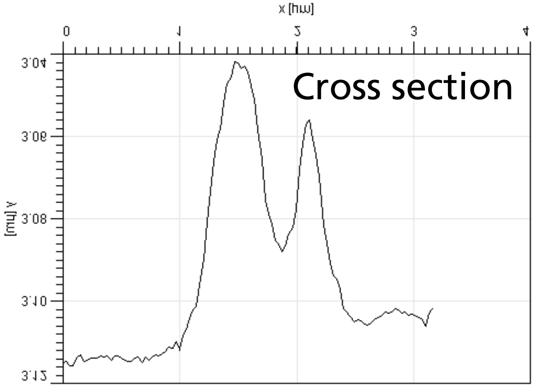
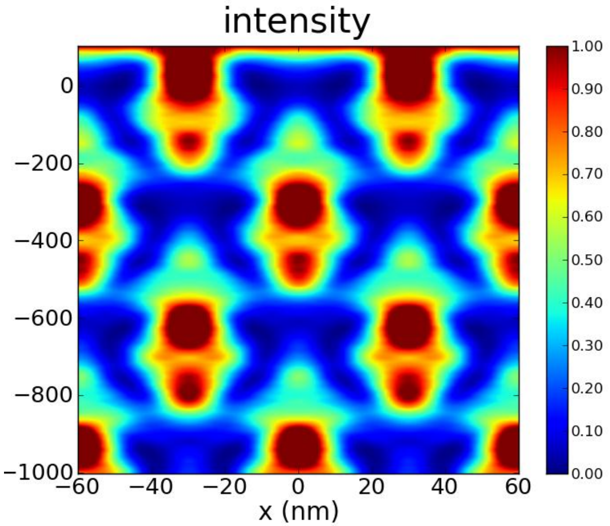
- **Experiment** (1 min, 15µm gap, PMMA)

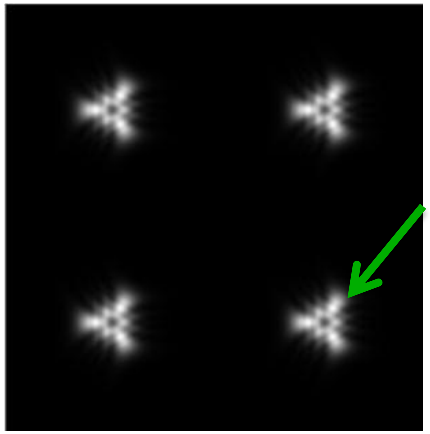


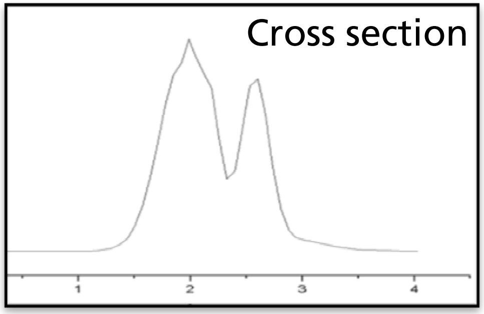




30 nm hp Talbot carpet

- **Simulation** (Aerial image at 15 µm gap)



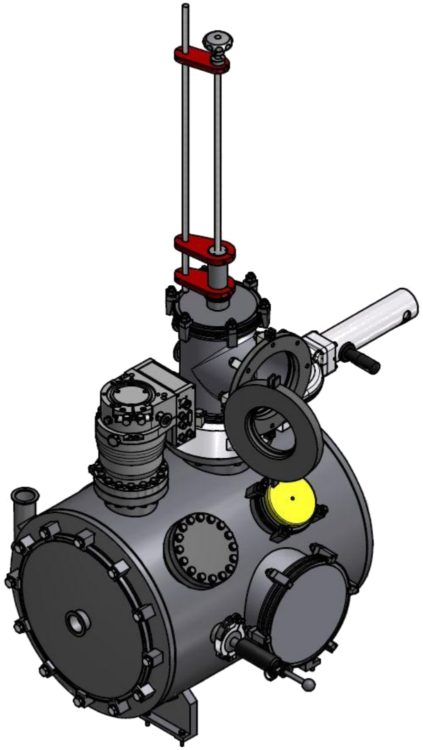


✓ Simulations show good correlation with experimental results

Summary

- EUV Interference lithography is a powerful tool for cost efficient patterning of nanoscale periodic arrays
- Optimized high power gas discharge source can be effectively used as a source for EUV-IL
- Talbot lithography is the most efficient solution for nanopatterning with sources of limited coherence.
- Nb-based transmission masks can be used as an universal solution for interference lithography with wavelength between 6 and 15nm
- The resolutions down to sub-10nm are possible, limited by mask quality and resist performance

EUV-IL exposure tool for 4“ wafers



- Input power 5.6kW
- Pinch radius 100µm
- 100W/(mm^{2}sr) brilliance

  at 10.9 nm
- 65mm x 65mm exposable
- Single field size > 4mm^2
- Field exposure time < 30s @ 30 mJ/cm^2

Acknowledgements

RWTH Aachen:

Dr. Larissa Juschkin, Sascha Brose, Hyun-su Kim, Prof. P. Loosen, Prof. Th. Taubner

Fraunhofer ILT:

Dr. Klaus Bergmann, Dr. Marcus Benk

Forschungszentrum Jülich

IBN-1:

Prof. Detlev Grützmacher, Dr. Jürgen Moers, Klaus Wambach, Dr. Gregor Panaitov,
Dr. Gregor Mussler

IBN-PT:

Dr. Stefan Trellenkamp, Elke Brauweiler-Reuters, Karl-Heinz Deussen, Alfred Steffen, Hans Wingens, Jürgen Müller, Bernd Hermans, Jana Mohr, Stephy Bunte