Opportunity to extend EUV lithography to a shorter wavelength

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Agenda

- Roadmap
- Challenges and opportunities
- Status
- Summary & conclusions

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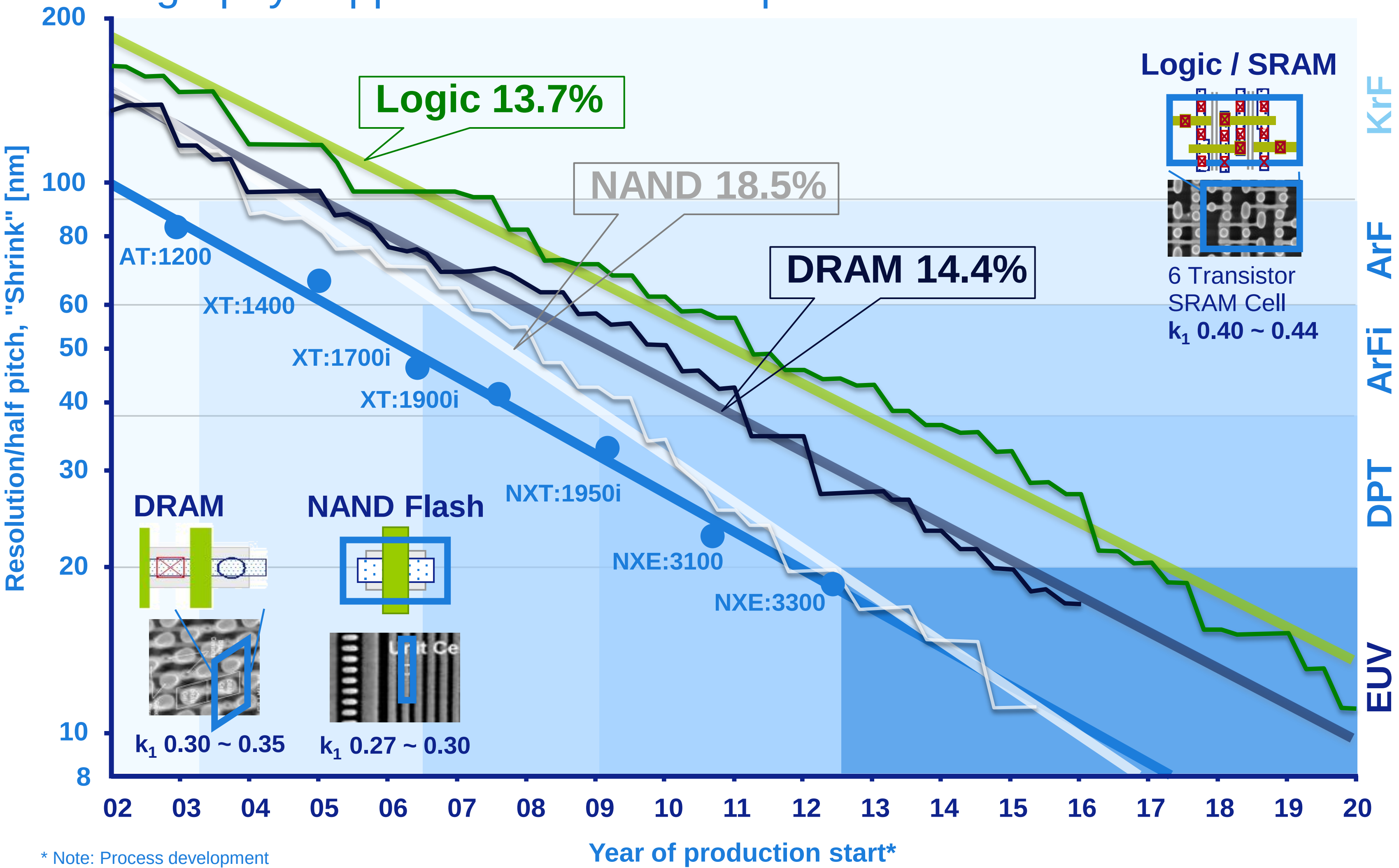
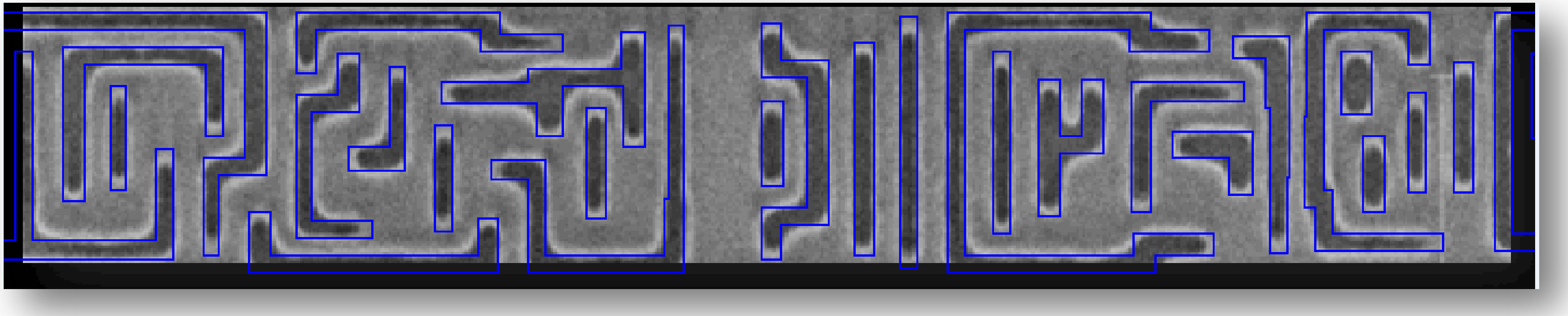
Industry roadmap towards < 10 nm resolution

Lithography supports shrink roadmap



* Note: Process development
1.5 ~ 2 years in advance updated 8/11

EUV enables 14nm node with large UDOF

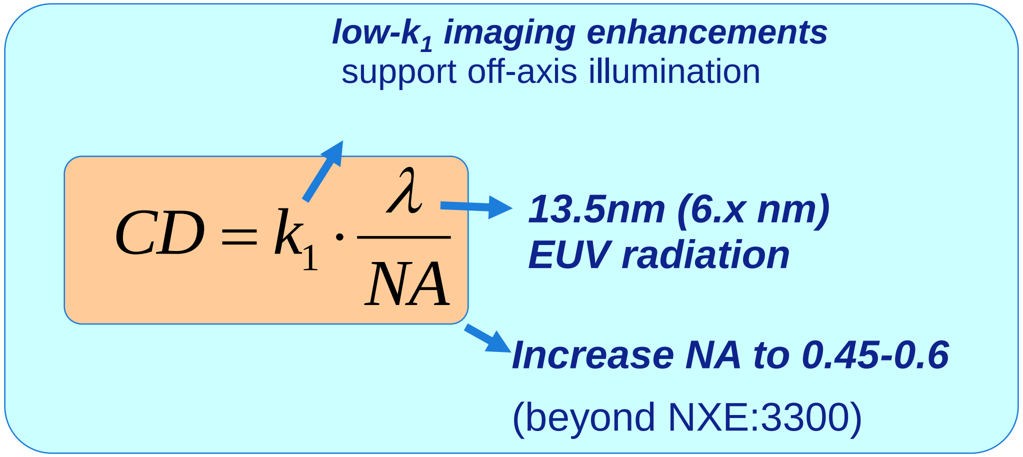


14nm node ARM M1 clip without OPC, 46nm minimum pitch, exposed on an NXE:3300B with conventional illumination

	EUV	ArFi
	Single exposure	Double patterning (LELE)
Best HV focus difference	<10nm	up to 60nm
Usable depth of focus	>100nm	50nm

EUV lithography is optical lithography…

- Resolution scales with aperture (starting at 0.25) and illumination wavelength
  - 13.5nm → 14x leverage to 193nm,
  - Eg 6.x -> 2x leverage on 13.5 nm, and is theoretically extendible (beyond 7 nm in SP).



low-k_1 imaging enhancements
support off-axis illumination

$$CD = k_1 \cdot \frac{\lambda}{NA}$$

13.5nm (6.x nm) EUV radiation

Increase NA to 0.45-0.6
(beyond NXE:3300)

13.5 nm

🟩 imaging possible
🟧 NA too small for imaging

k1	0.33	0.45	0.6
22 nm	**0.54**	**0.73**	**0.98**
18 nm	**0.44**	**0.60**	**0.80**
16 nm	**0.39**	**0.53**	**0.71**
13 nm	**0.32**	**0.43**	**0.58**
10 nm	**0.24**	**0.33**	**0.44**
7 nm	**0.17**	**0.23**	**0.31**
6 nm	**0.15**	**0.20**	**0.27**

NA

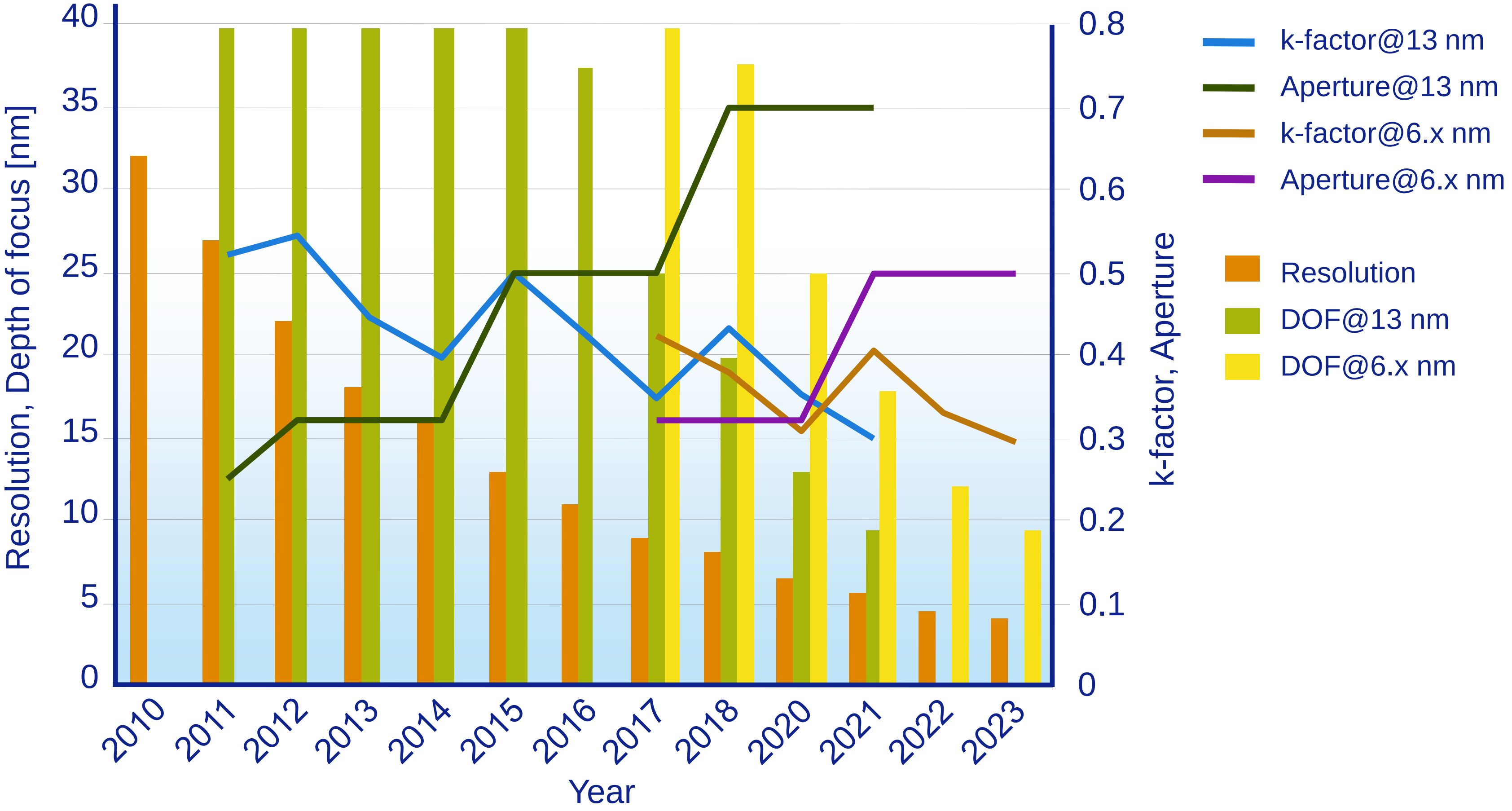
CD

6.x nm

k1	0.45	0.6
7 nm	**0.47**	**0.63**
6 nm	**0.40**	**0.54**
5 nm	**0.34**	**0.45**

Extension of optical lithography beyond 7 nm with a new wavelength and single patterning is theoretically possible

Opportunity to extend of EUV down to sub 7 nm possible



6.x nm can provide matching DOF at lower CD than 13.5 nm lithography

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- Challenges and opportunities
    - Wavelength choice
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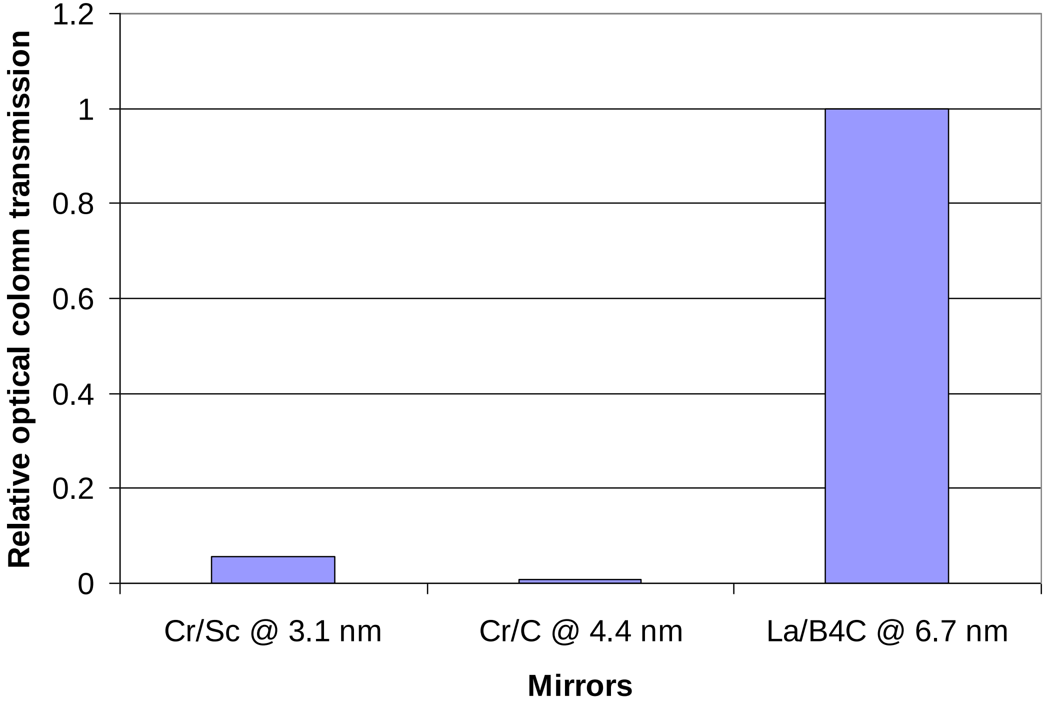
Are there other viable wavelengths and mirror multilayers for lithography

- Materials, Wavelengths, Theoretical transmission (TT) per mirror as calculated with CXRO
  - Cr/Sc @ 3.1 nm -> TT= 60%
  - Cr/C @ 4.4 nm -> 50%
  - La/B4C and La/B @ 6.x nm -> < 80%
- Optical column transmission (10 mirrors)



6.x nm is the choice:

- Best transmission
- Easier manufacturing (thicker layers)

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- Challenges and opportunities
    - Imaging, MLM technology, Source
- Status
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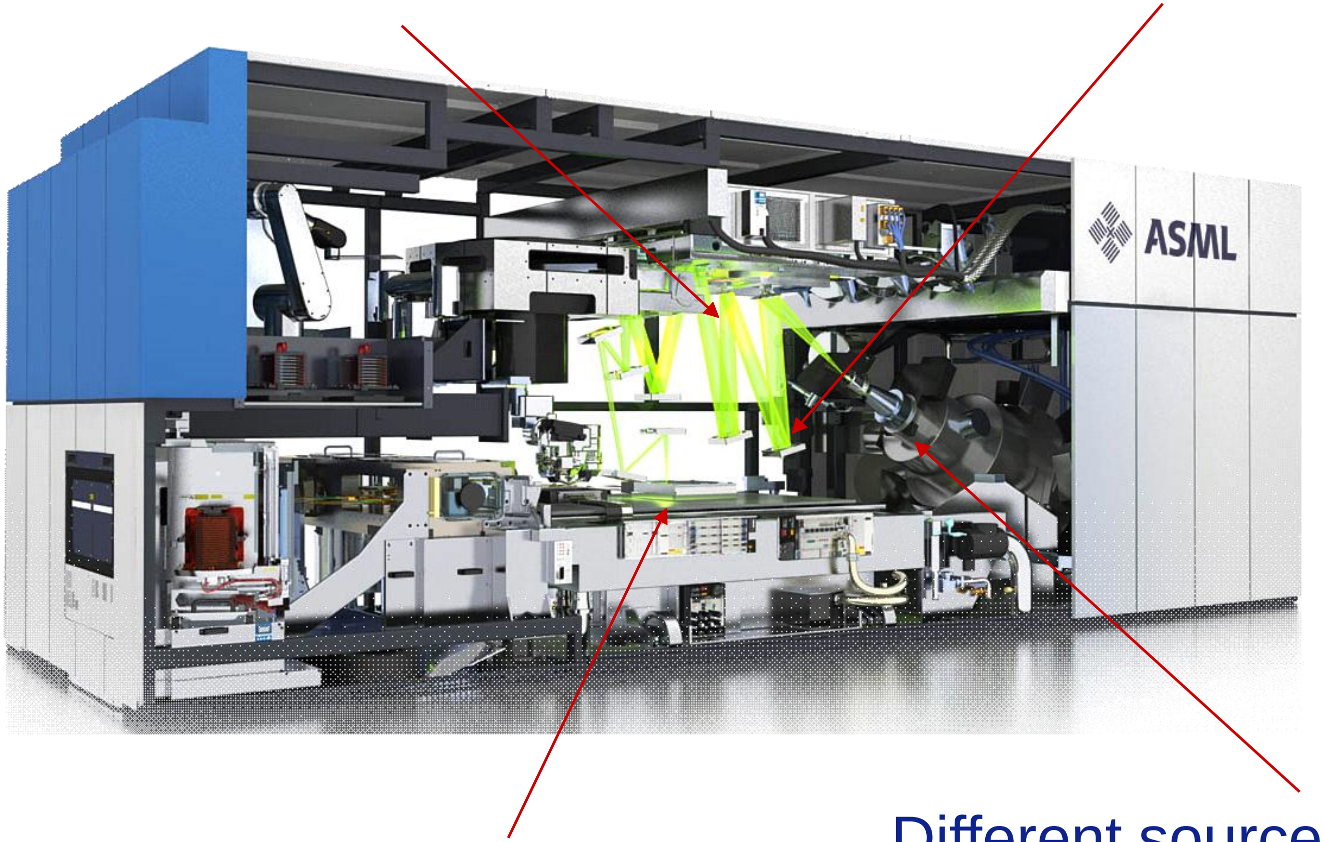
Introduction to changing source wavelength: List of challenges

- **Challenges to Imaging**
  - Flare level scales $\propto 1/\lambda^2$
  - Bandwidth of a single mirror $\Delta\lambda/\lambda$(Mo/Si)=4% → $\Delta\lambda/\lambda$(La/B)<1%
  - Bandwidth of the optical column $\Delta\lambda_\Sigma/\lambda$(Mo/Si)=2% → $\Delta\lambda_\Sigma/\lambda$(La/B)=0.6% (or ~0.4% for LaB_4C)
- **Challenges to MLM Technology**
  - Match reflectivity with existing 13.5 nm MLM (max ~70%),
  - Smaller layer thickness $\propto \lambda$,
  - Requirements to interlayer diffusion $\propto \lambda$
  - Larger number of bi-layers per multilayer
- **Challenges to Source**
  - New fuel is needed with the matching CE (3-5%) in the narrow bandwidth
- ***Resist***
  - Quantum efficiency of current EUV resist will decrease due to lower absorption of 6.7nm(186eV) photons vs 13.5nm(92eV) photons
  - Potential shot noise increase

What changes for a new wavelength



Different lens layout

Different coating

Possibly new resist

Different source fuel

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    - Imaging with 6.7 nm
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First optical exposures of resist with λ=6.x nm

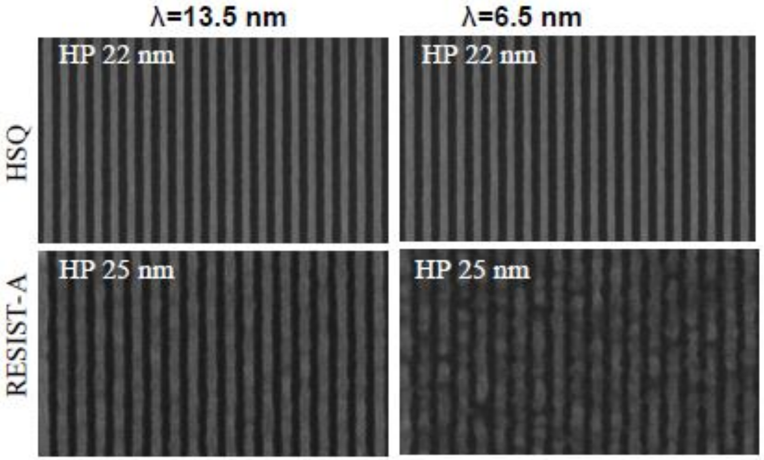
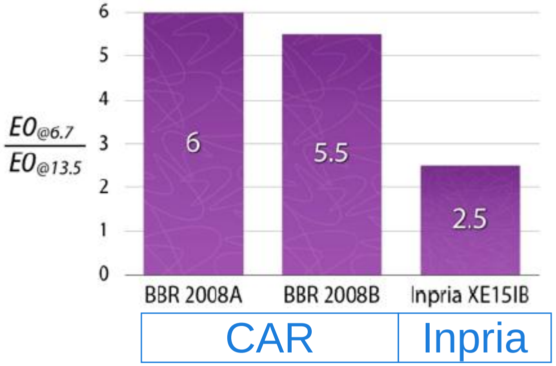


Figure 15. SEM images of HSQ and *Resist-A* resists patterned with EUV and BEUV interference lithography.

From Y. Ekinci, et al. Proc. of SPIE 83220W-1 (2012)

Dose to clear



From C. Anderson, et al. Proc. of SPIE 832212-6 (2012)

- Inorganic resist show similar performance at λ=13.5 and λ=6.5 nm
- Shot noise for 6.x nm is inherently worse thus dose needed might be higher

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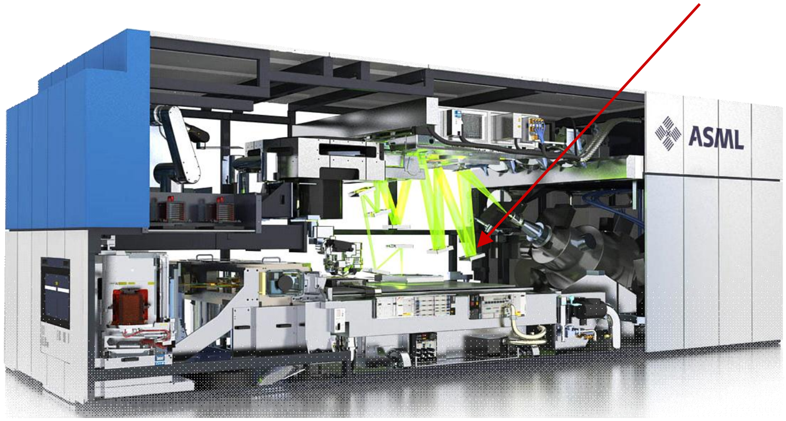
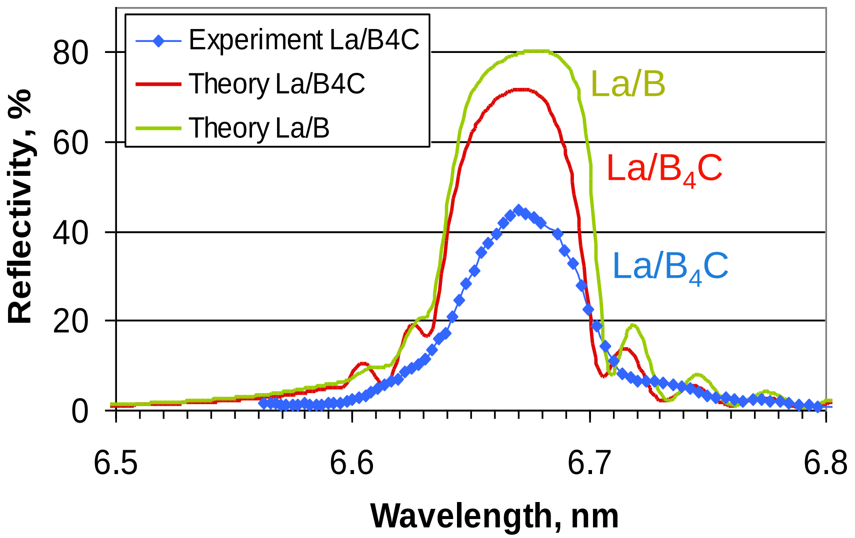
  - Multilayer mirrors and optical design considerations
- Summary & conclusions



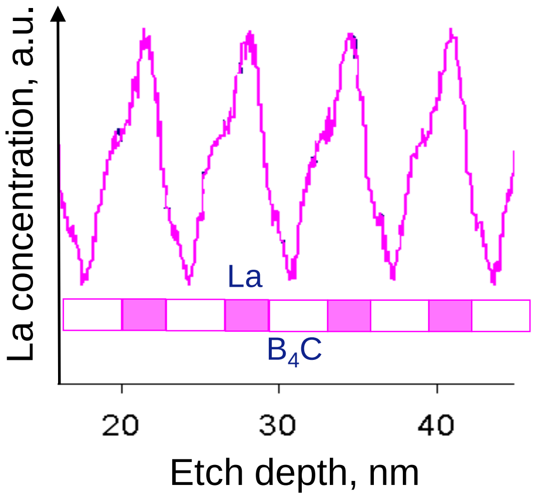
Different coating

First attempts to manufacture La/B_4C MLM at 6.x nm

MLM reflectivity (200 bi-layers)



Depth profile of La in MLM shows intermixing of La with B_4C*



- Theoretical maximum for La/B_4C R~71-73% @6.62 nm
- Theoretical maximum for La/B R~82% @6.65 nm
- For reference for 13.5 nm it is ~72%

- Low reflectivity is due to poor interface width~0.8 nm, while <0.3 nm is required. Depth profile analysis shows La intermixing with B_4C.

→ Better control of interfaces and material density is required

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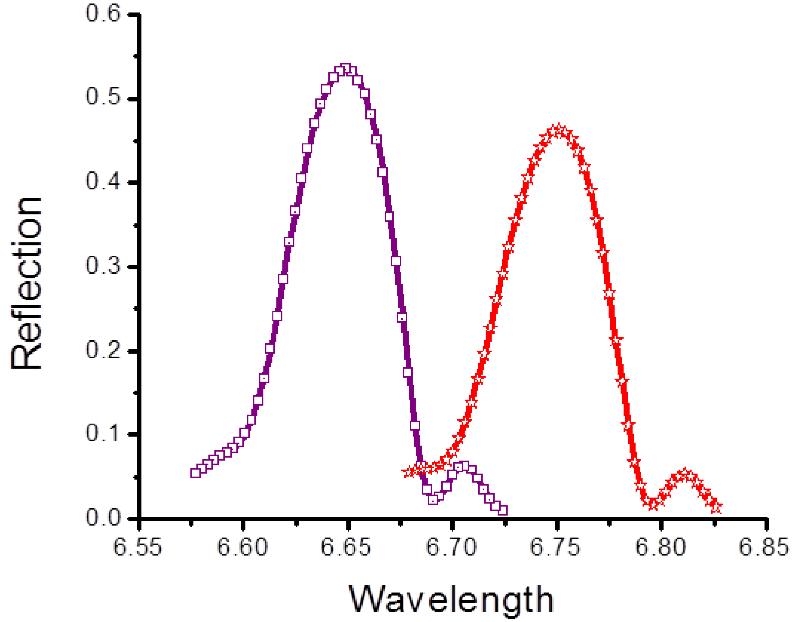
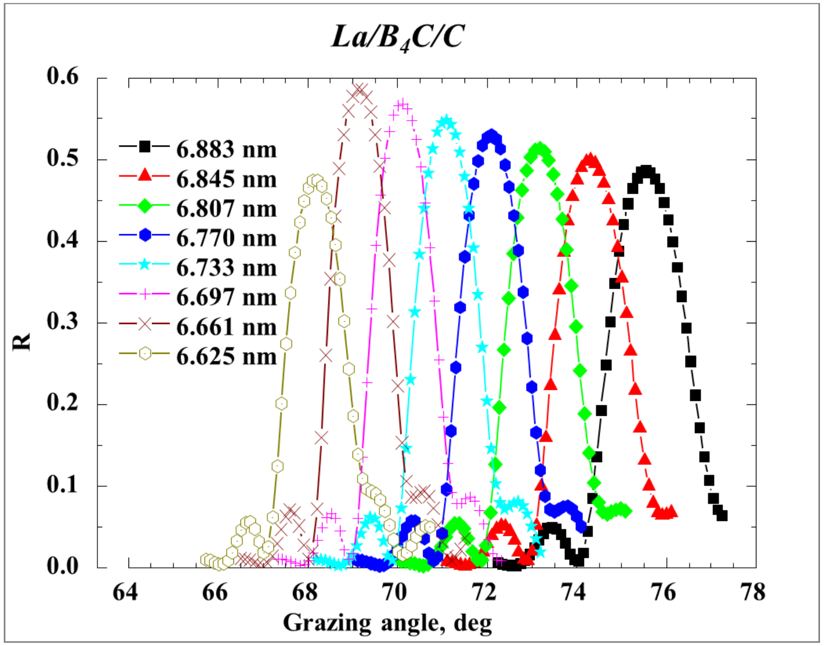
* Smaenok et al, 2010 EUV source workshop, Dublin

MLM reflectivity: last year achievements

175 period LaN/B MLM:
the reflectivity highlights
(@ 85 deg)



MLM with carbon anti-diffusion layers,
fabricated at IPM RAS / X-Ray.

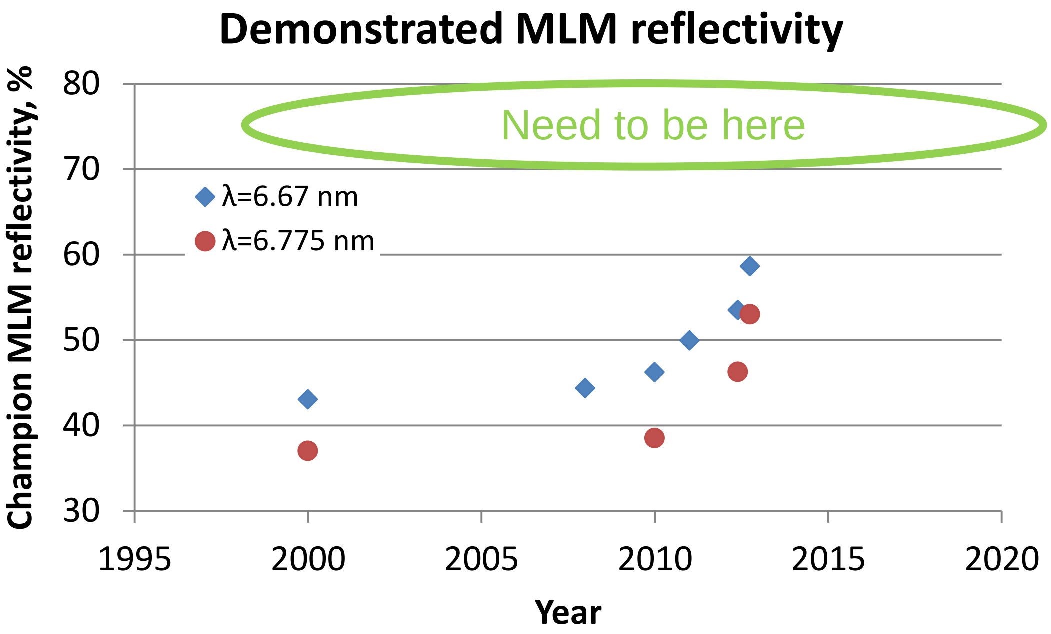


Measurements performed by F. Schaefers at BESSY-2.

Makhotkin et al, this conference

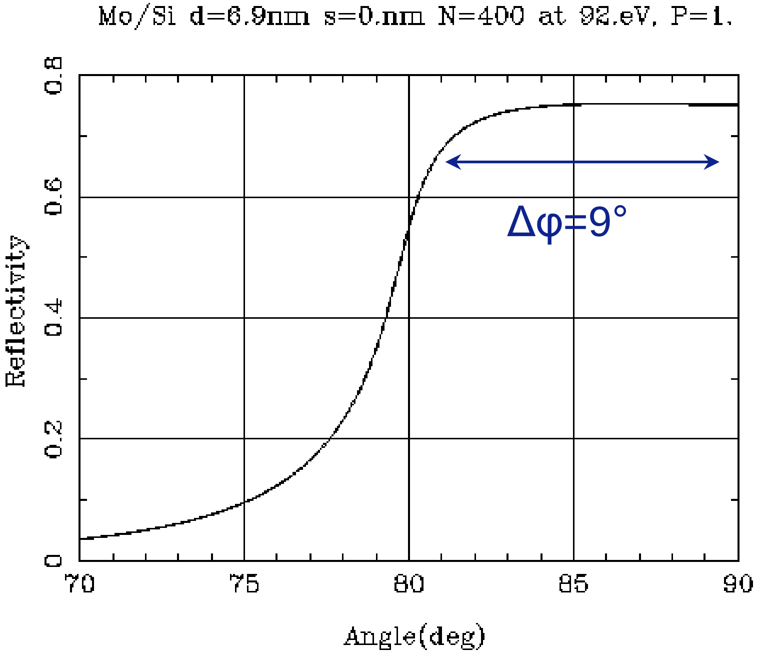
Achieved reflectivity is improved in last years (40% to 58%) but yet far form 70+%

MLM reflectivity progress through years



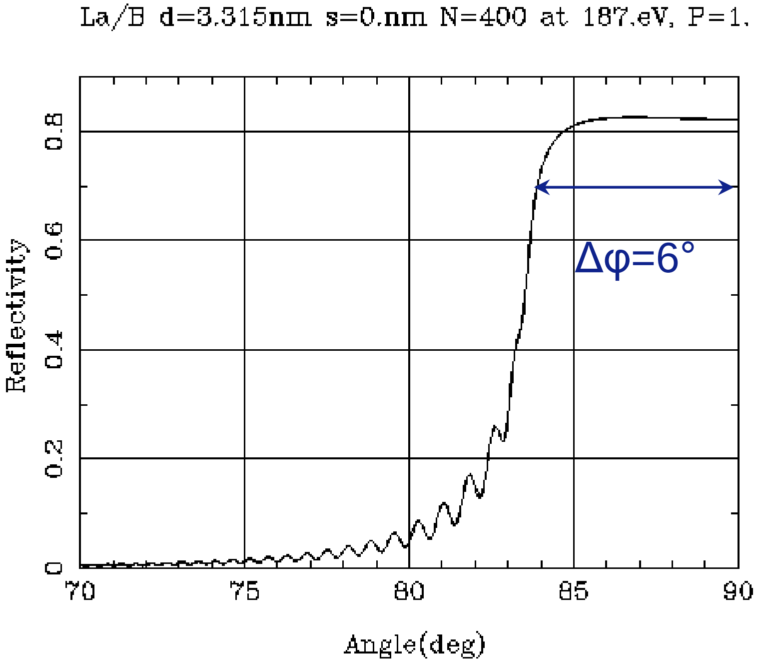
Achieved reflectivity is improved in last years (from 40% to 58%) but yet far form 70+%

Angular width of MLM: 13.5 vs 6.7 nm



Mo/Si d=6.9nm s=0.nm N=400 at 92.eV, P=1.

Δφ=9°



La/B d=3.315nm s=0.nm N=400 at 187.eV, P=1.

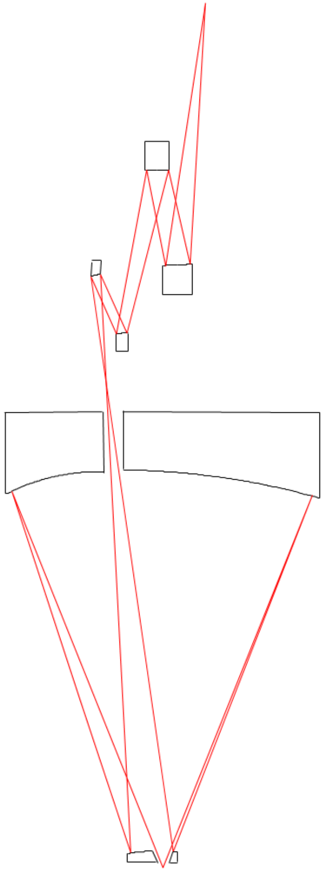
Δφ=6°

La/B MLM has ~1.5x lower angular band than Mo/Si MLM:

- Lower mask reflectance for angles Δφ>6° (Reflectivity decreases by 2x for NA=0.6)
- Impact on POB design -> smaller angle variation possible over the mirror
- Source, illuminator mirror losses are acceptable

POB design with NA=0.35 (Zeiss)

Example of a possible new design



Basic design:

- Off-axis design (6 mirrors)
- One of the mirrors is critical with angle spread is too large for λ=6.7nm
- Integral reflectivity of the critical mirror ~ 10%

Re-design of projection optics is needed

At least one of the mirrors is critical to the angular spread

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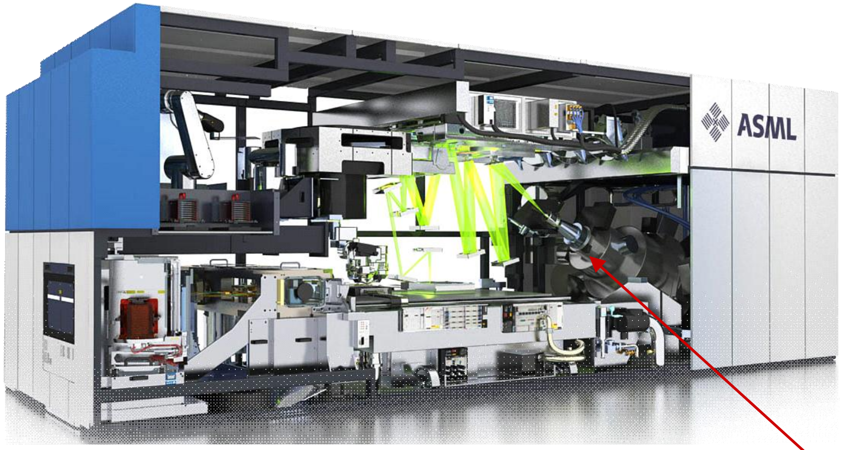
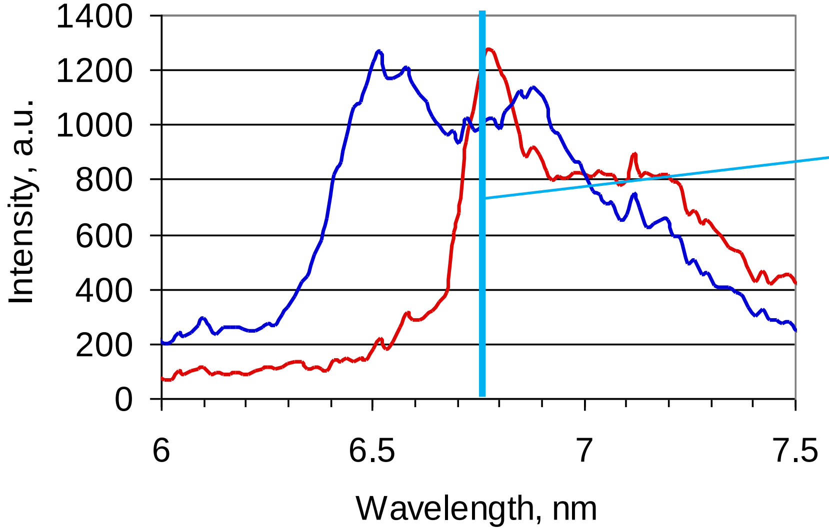


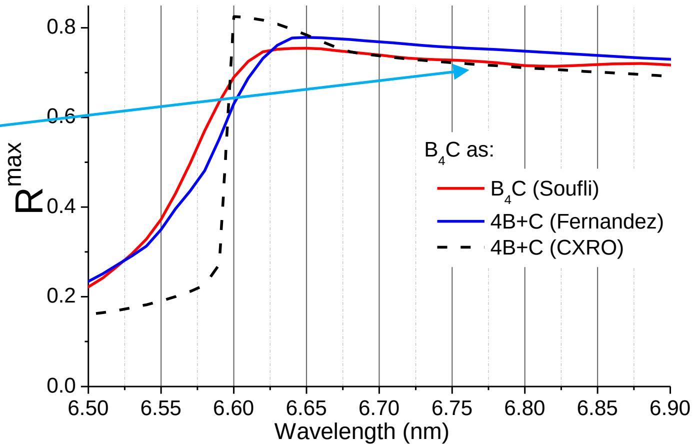
Different source fuel

Choice of source fuel

LPP spectra of Gd and Tb



Peak reflectance spectrum of 1 La/B_4C MLM



From I. Makhotkin, et al. Proc. of SPIE 8322 - 38 V.2 (2012)

- Optical constants of B close to the absorption edge at 6.6 nm are debated. Optimum wavelength for throughput λ_{opt}=6.6-6.65 nm
- Tb and Gd provide comparable CE at λ_{Tb}=6.5 nm; λ_{Gd}=6.775 nm. Peaks are shifted with respect to optimum of La/B optics
- Gd is widely available cheap material (unlike Tb) → λ=6.775 nm is preferred
- Large uncertainty exists w.r.t. reflectivity of La/B_4C around 6.7 nm, eg for Gd maximum:
  - Based on CXRO n,k: mismatch of the wavelength might cause 3x total optical thrpt loss, while
  - Based on n,k measurement by R. Soufli: it is 1.3-1.5x

Source and conversion efficiency

- Based on model of Rzline* (Gd and Tb) in band CE for 6.7 nm is ~2x lower than that for 13.5 nm
- Up to now in the experiments with flat target it seems to be true

Measured CE data for Gd at 6.775 nm in 0.6% band for various conditions (Single shot!)

Target geometry		CO2 (70 ns)	YAG (40 ns)	YAG (2 ns)
Flat	%	0.9	0.1	0.9
3D mesh		?	0.1	0.6
Alloy		0.5	0.3	0.4
Colloid		1	0.3	?
Perforated foil		1.8	?	?

Max achieved CE=1.8% (vs 4-5% for 13.5 nm)

ISAN

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* Novikov et al, 2010 EUV source workshop, Dublin

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    - Vacuum environment
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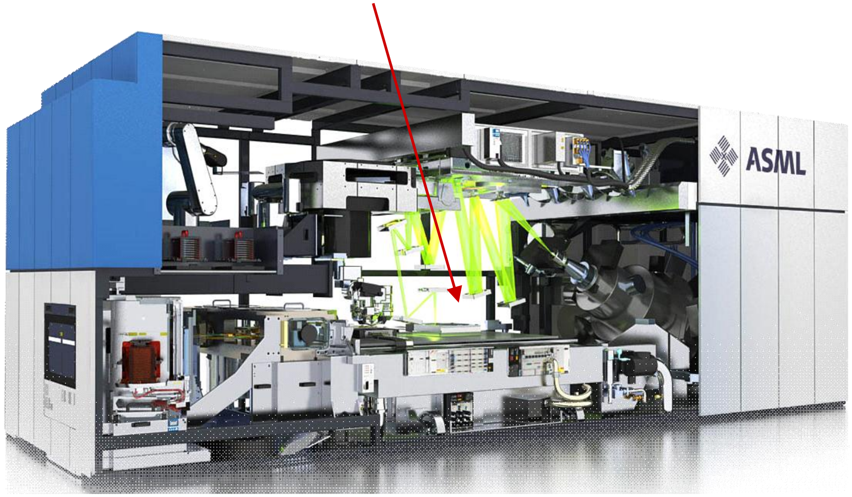
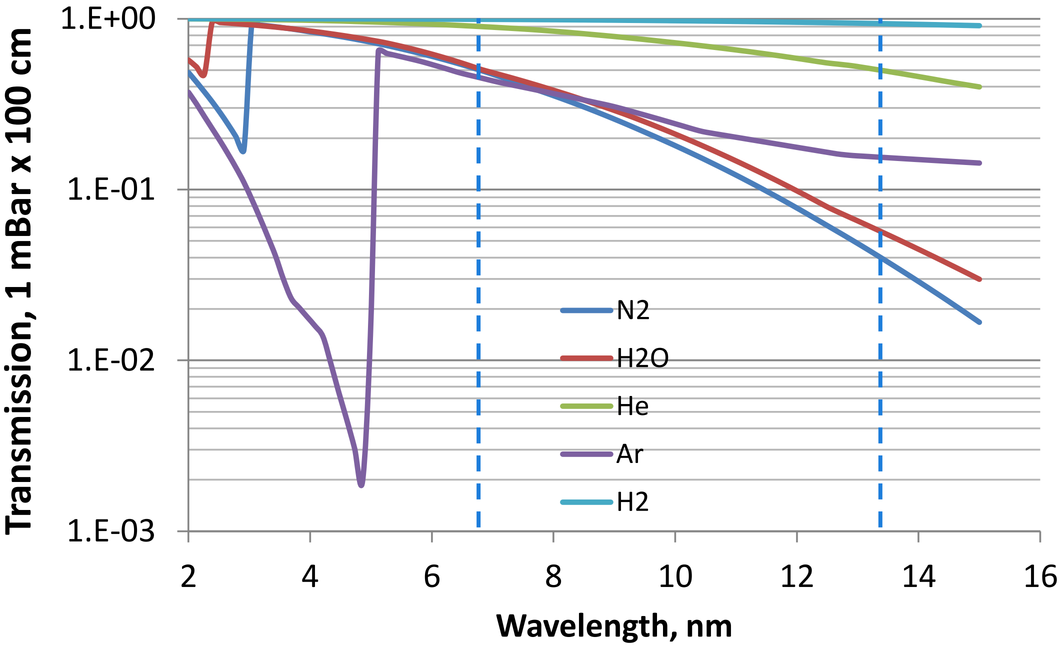

Vacuum environment

Transmission loss on gases and contamiination
6.x nm vs 13.5 nm



- 6.x nm radiation shows quite low absorption in
  - Gas environment
  - Contamination layers
- Integral improvement up to 1.3x is feasible

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Throughput comparison 13.5 and 6.x systems

Theoretical CE 1:2 for 6.x and 13.5

Theoretical Optical throughput 3x (for LaB) & 1x (LaB_4C) for 6.x vs 13.5 nm

Additional optics losses 1.5-3x for 6.x vs 13.5 nm

Vacuum environment transmission 1.3x for 6.x vs 13.5 nm

For the same throughput ~1x-5x** more power input into the source is needed

* Resist sensitivity is taken comparable ** Uncertainty in ML performance is very high

Summary and conclusions

- If chose among other wavelengths for a next step after 13.5 nm 6.x nm is the most promising
- To become a viable option for lithography a number of challenges for 6.x nm has to show a rapid improvement:
  - ML coating
    - Though ML has a potential of for high peak reflectivity (up to 80%) for La/B but,
    - Currently demonstrated reflectivity LaB_4C is 58.6% @70 deg and has to become scalable yet to ~70+% (the small bandwidth of ML will not allow to reach this peak reflectivity in real optical systems)
  - EUV source
    - Theoretically CE for 6.x nm is ~2x lower to that of 13.5 nm,
    - Single shot CE 1.8% has been demonstrated
    - Scalability to the real source value still to be proven
    - 1x-5x more power input is needed to match the overall throughput losses
  - Actual available bandwidth limits the overall transmission of optics. Thus new optical designs to account for the small bandwidth are needed
  - Optimization of EUV source spectrum with ML optics is required
  - Extendibility of resist to 6.x nm has to be proven

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