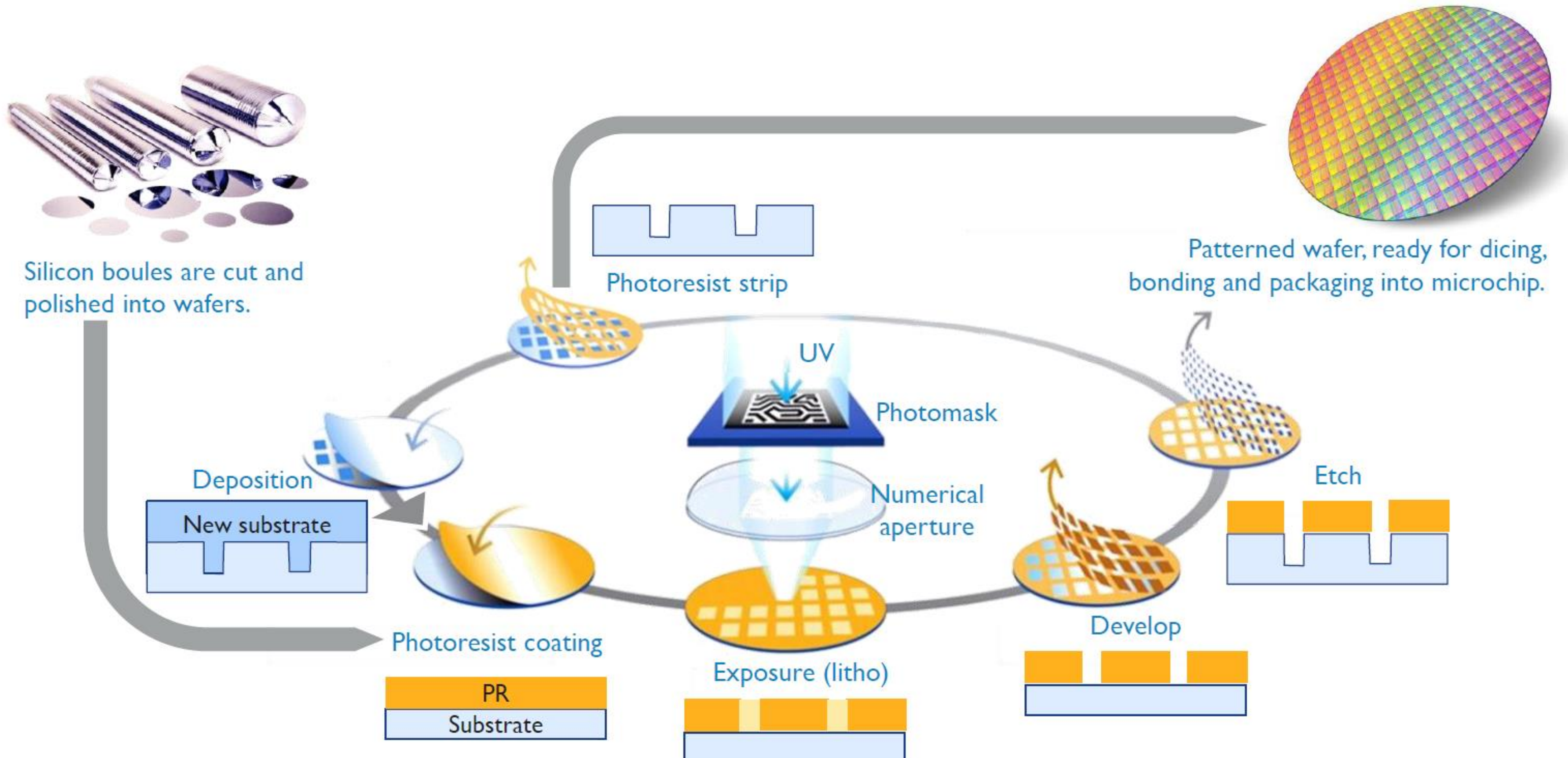
Lecture#4:

Photolithography (2)
: Nanolithography

[Reminder] Micro-lithography

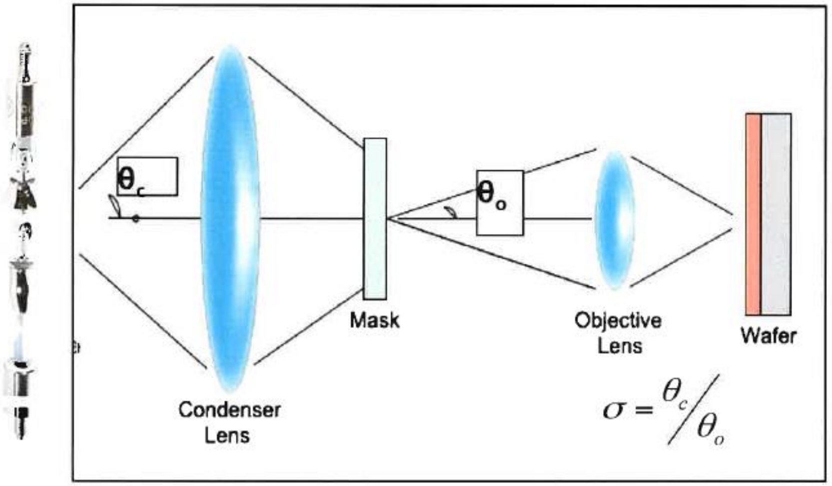
Photolithography (2): Nanolithography

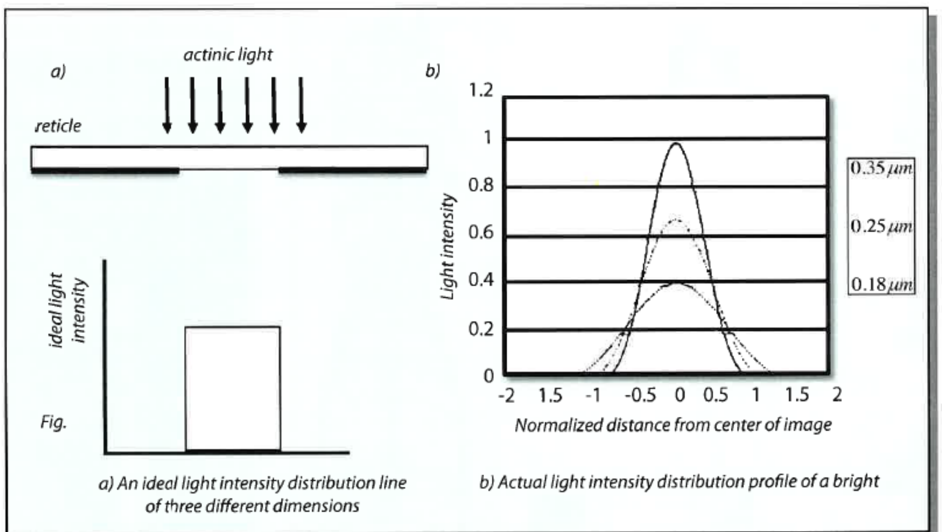
- **General lithography**



Adapted from den Boef, A., Surf. Topogr.: Metrol. Prop., 2016.

Photolithography (2): Nanolithography



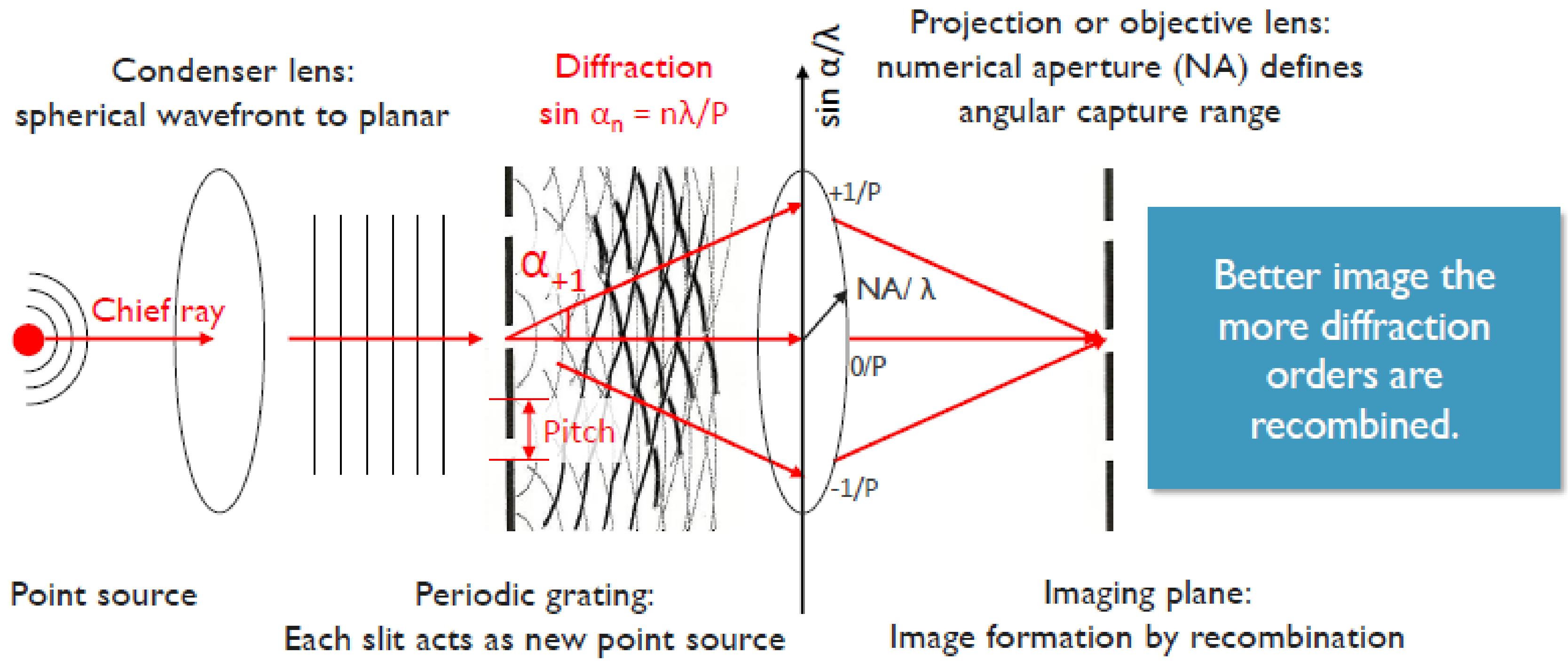


- Illuminating actinic light
- Reticle
- Lens
- Photoresist

<Points to consider for nanolithography>

- The edge of the feature is not well defined.
- Even if the feature could be printed, linewidth control becomes a problem.
- If slope becomes too degraded, imaging becomes impossible.

Fourier optics & diffraction gratings

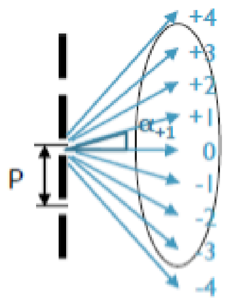


http://zeiss-campus.magnet.fsu.edu/print/basics/resolution-print.html

- Diffraction orders can be recombined, as they are coherent, since they originate from the same point source.

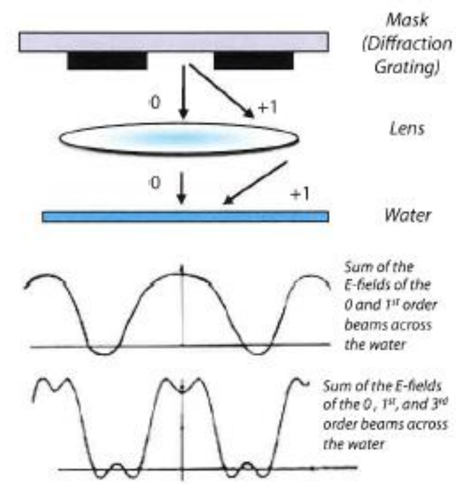
- If the projection lens of a lithography system has an NA that is large enough to capture only the “0-order beam” no pattern is formed.

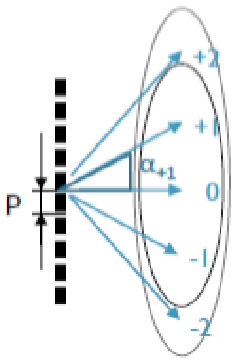
Diffraction limits



$\sin \alpha_n \downarrow = n\lambda/P \uparrow$

Large pitch → small α
Easy image formation, as many diffraction orders are captured by NA





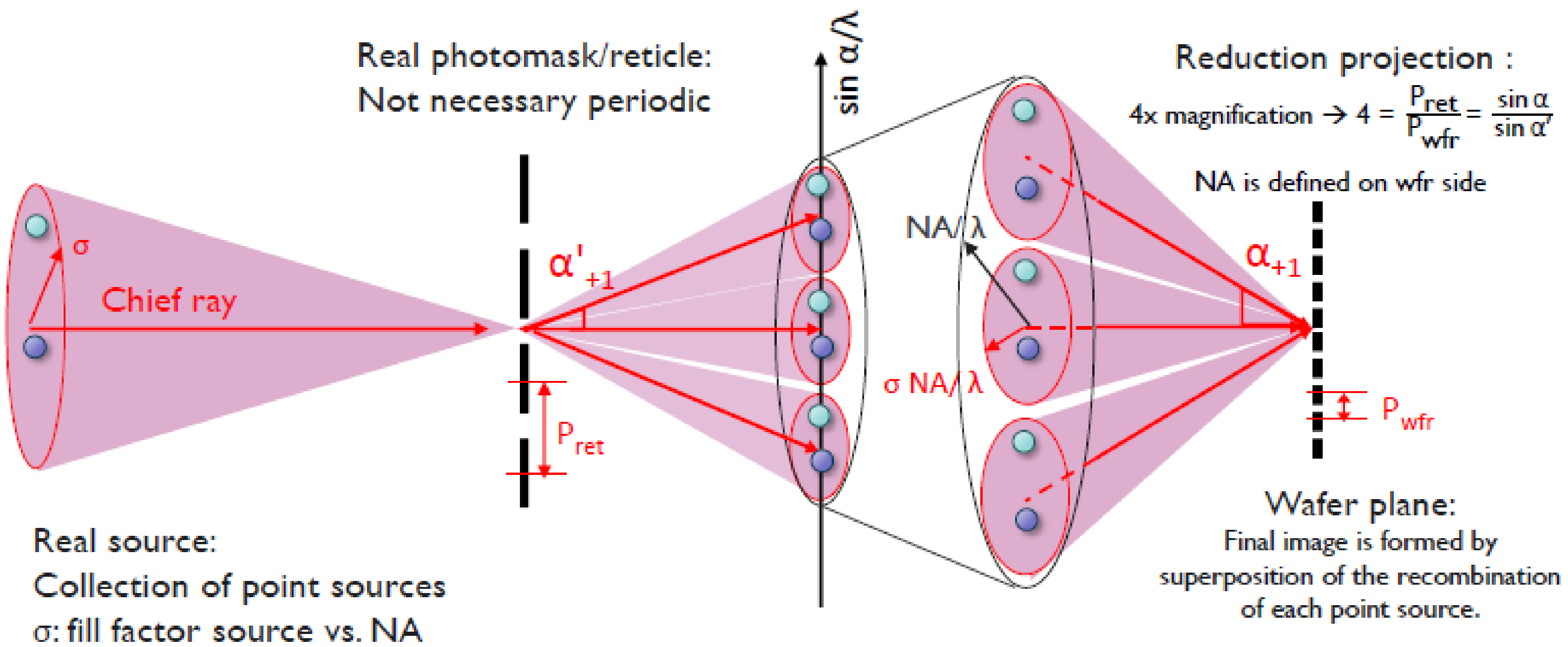
$\sin \alpha_n \uparrow = n\lambda/P \downarrow$

Small pitch → large α
Image formation requires at least 2 orders to be captured (e.g. 0 and +1).
Larger NA can help capturing more orders.

- If at least one additional beam can be captured, after passing through lens and arriving at the wafer surface, the two beams will interference and produce a pattern.
  => The more beams a lens can capture, the more closely will the images resemble mask features.

- But, beyond a minimum pitch, a lens with a given λ and NA will not be able to image a grating pattern at all.

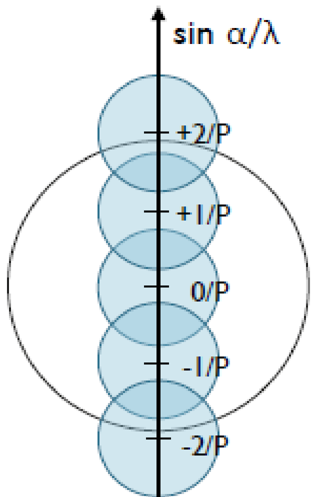
Issues



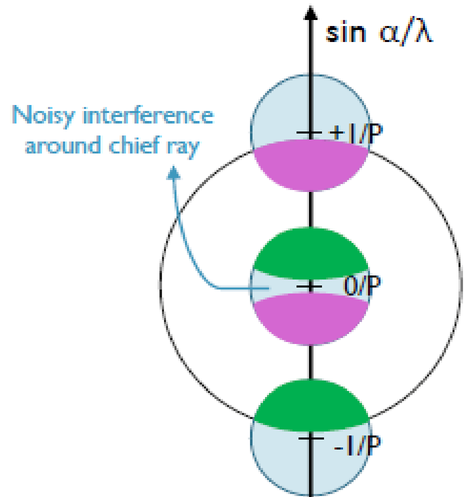
- Real source is only partial coherent.

General Image Formation (4) – Real Lithographic System

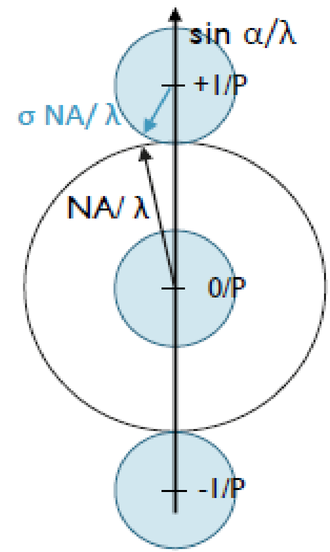
Photolithography (2): Nanolithography



Pitch >>> resolution limit



Pitch > resolution limit



$$\frac{1}{P} - \sigma\frac{NA}{\lambda} = \frac{NA}{\lambda}$$

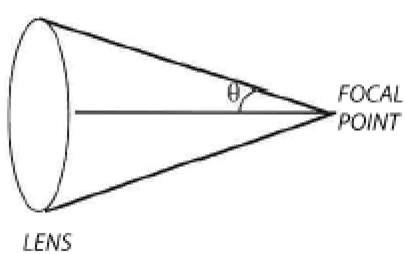
$$P = \frac{\lambda}{NA\,(1+\sigma)}$$

Theoretical res. limit

Practical resolution limit for half-pitch:
(spatial resolution)

$$R_{H.P.} = \frac{P}{2} = k_1 \frac{\lambda}{NA}$$

Process para. $k_1 > 0.25$

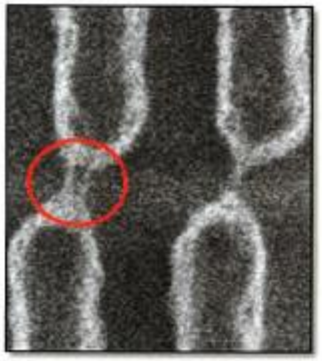


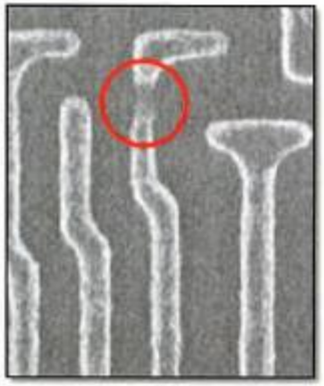
NA = Numerical Aperture = n • sin θ where θ is the collection angle of the lens and n is the index of refraction of the medium light passes through (n_{air}=1)

<Three key parameters for improving resolution>

- Lower K_1
- Shorter wavelength
- Higher NA (lager: more expensive lenses, fundamentally limited by geometry: sin θ < 1)

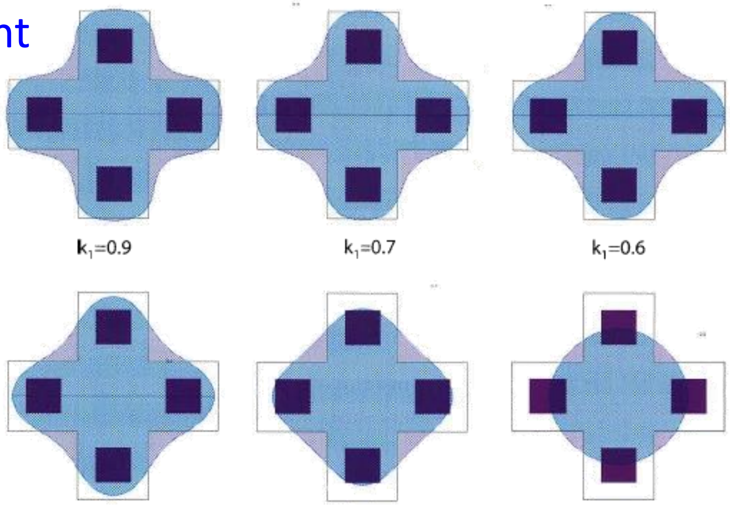
- **Low K_1 = high pain**





- Unlike λ and NA, there is no "K_1 knob" you can turn to increase resolution
  - K_1 is simply NA x $R_{H.P}$ / λ
  - For a fixed λ and NA, if you try to print smaller features, you are effectively working at lower K_1.

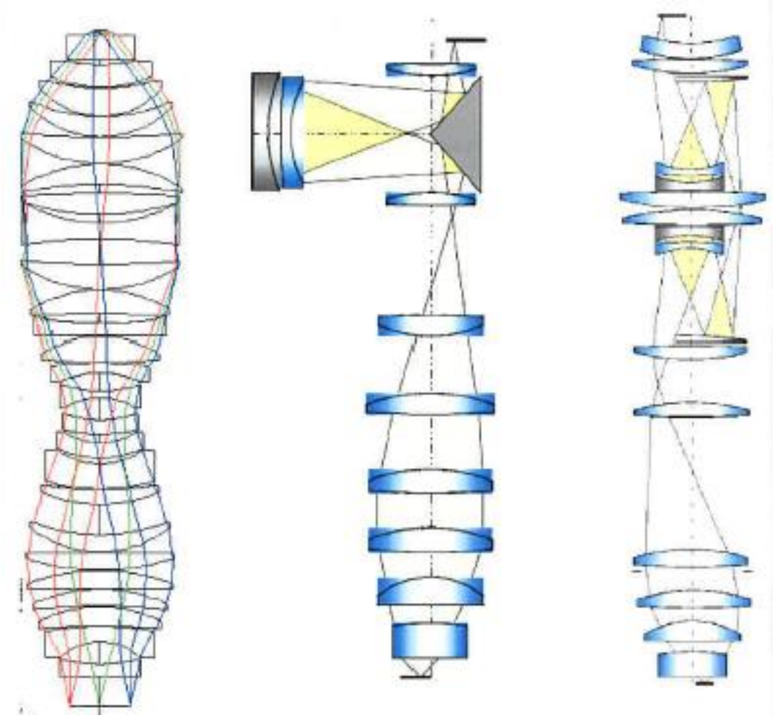
- As K_1 shrinks, the aerial image becomes worse
  - Low K_1 means trying to print good resist images with worse aerial image.
  - Higher probability of CD variation leading to shorts, breaks.



Higher NA Has Limitation

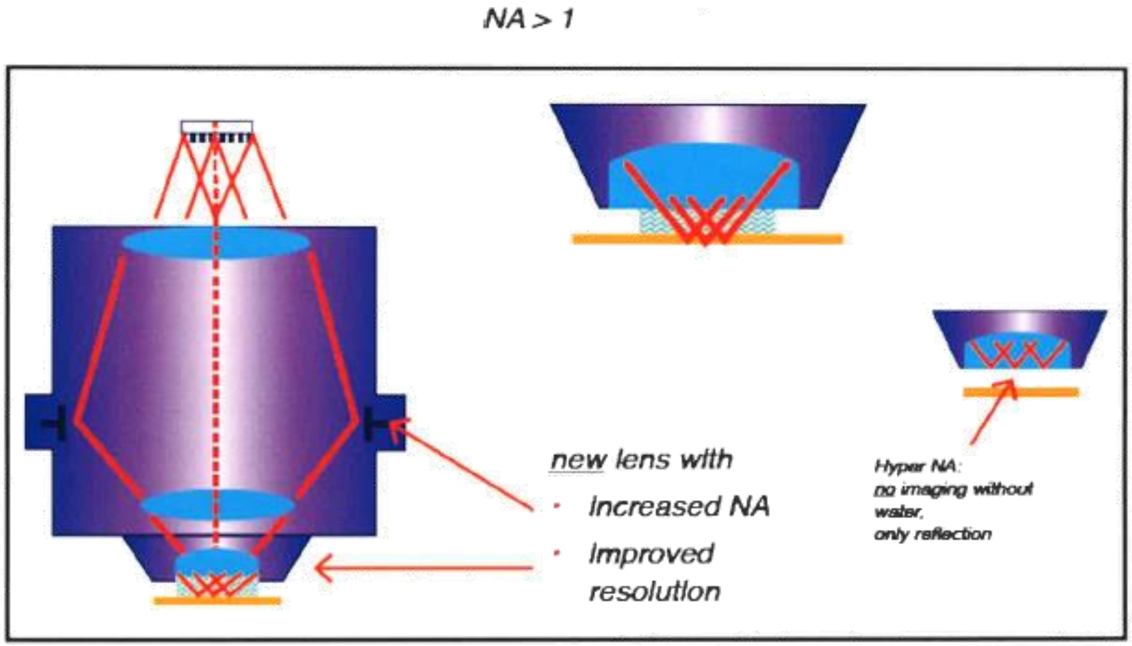
Photolithography (2): Nanolithography

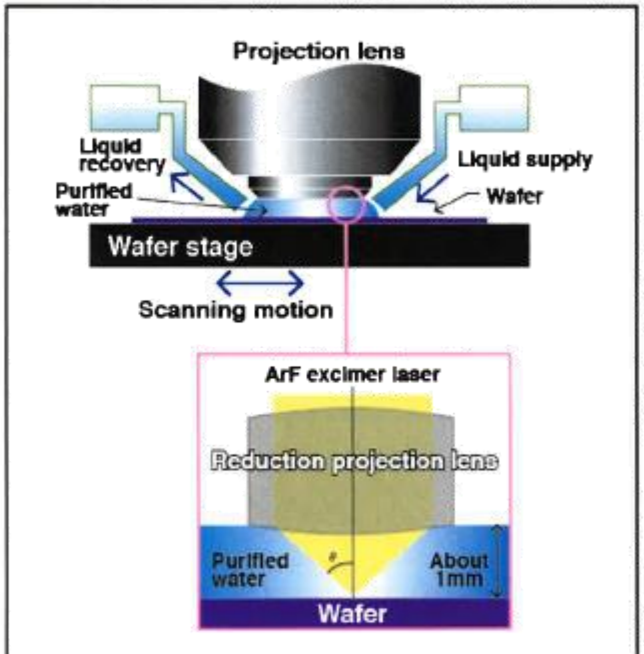
- **Lens complexity (193 nm)**



- Increasing NA
  - Lens design and fabrication now allow NA near 1 (~0.93)
  - There is no room left (fundamentally limited by geometry: sin θ < 1)
  - Lens increases in size and cost

Immersion lithography

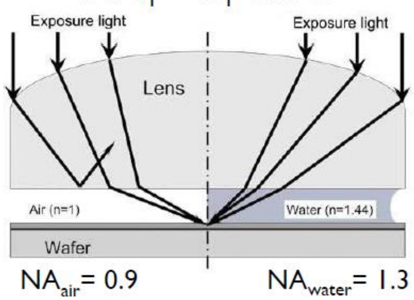




Immersion Lithography Model

Courtesy of Nikon

$$NA\uparrow = n\uparrow \sin \alpha$$

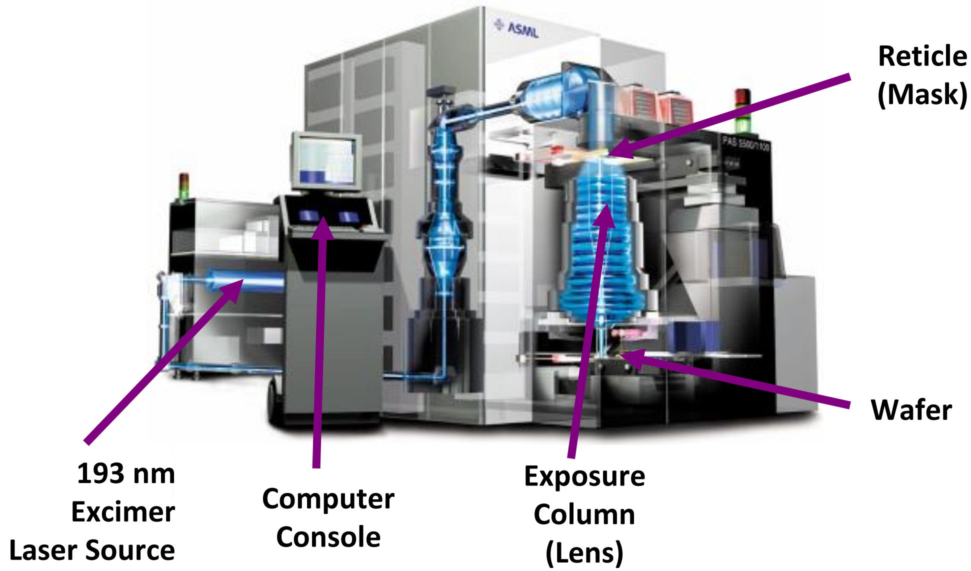


[Note] Production Lithography System

Photolithography (2): Nanolithography

Current Status for 14 nm node

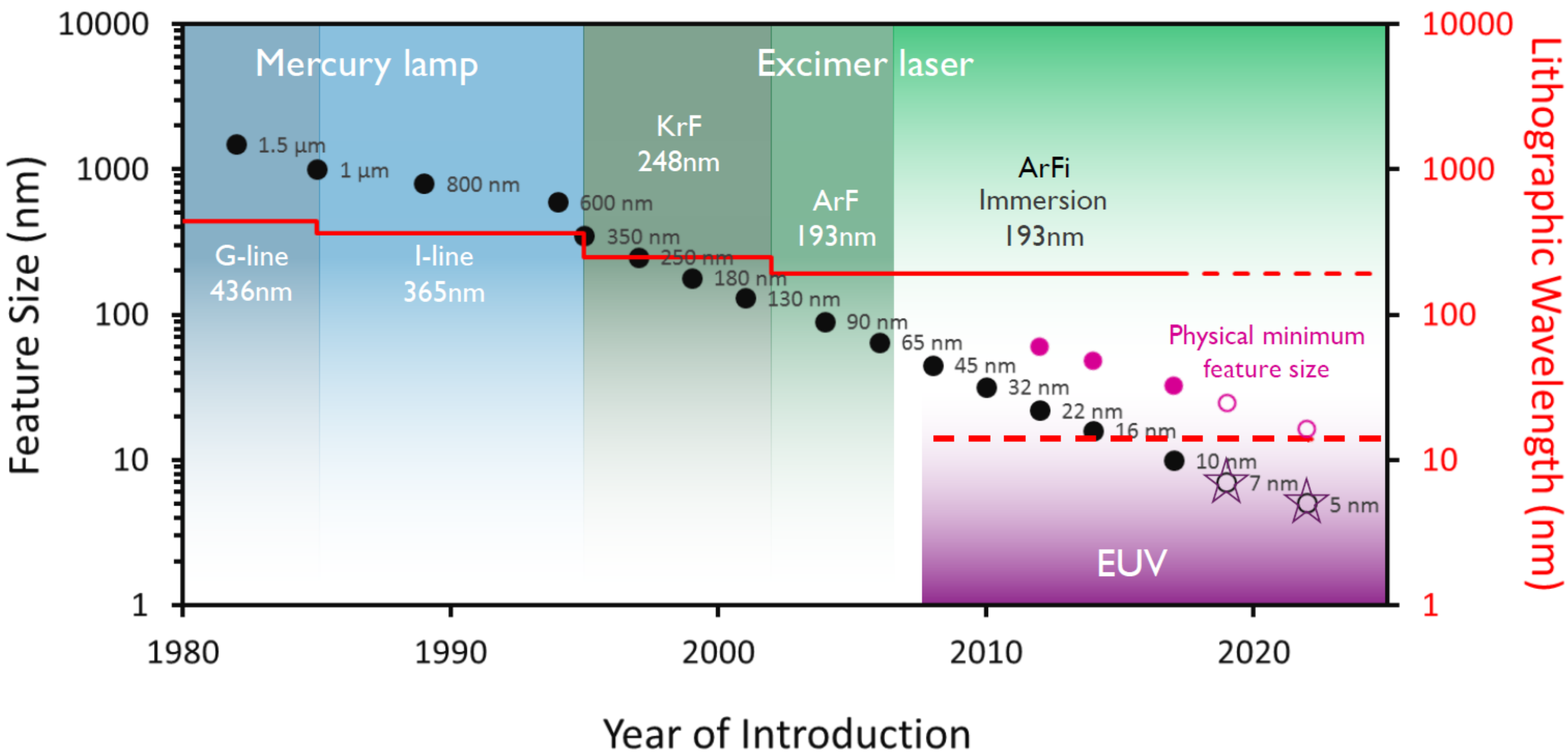
- ***Unchanged in ~ 9 years***
- *193 nm Step & Scan Exposure*
- *Chemically-Amplified Resist*
- *300-mm Silicon Wafer Substrates*
- *NA= 1.35*
  - *(Immersion Lithography)*
- *Resolution:*
- *~ λ/3 - λ/4*
- *Throughput:*
- *150-200 wafers/hour*



- *Leading edge fabs running "14 nm" processes, heading to "10 nm"*
- *Development underway for 7 nm node*

Photolithography (2): Nanolithography

- **Transitions in optical lithographic technologies**

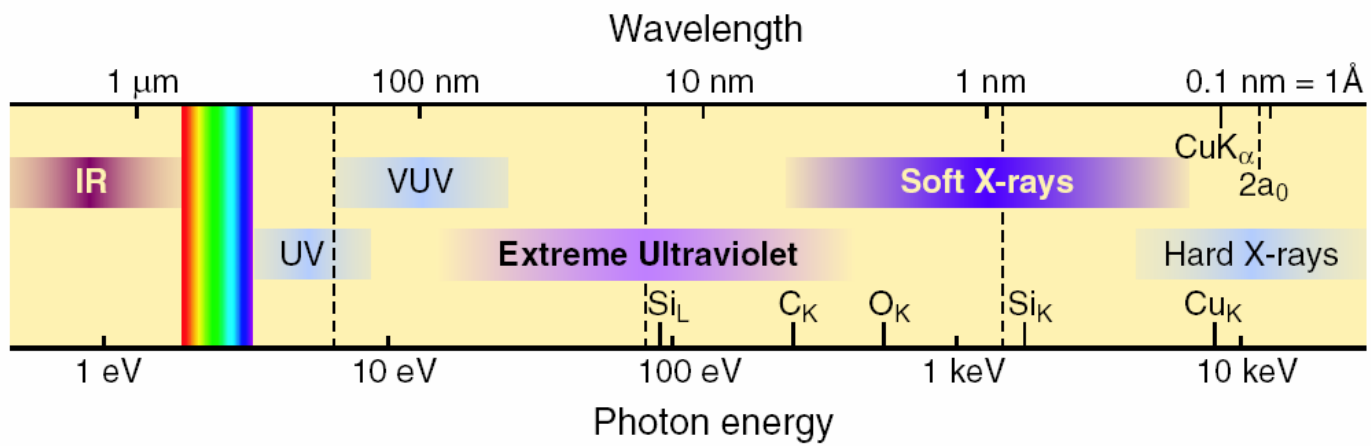


Data from WikiChip (https://en.wikichip.org/wiki/WikiChip).

What is EUV Lithography?

Photolithography (2): Nanolithography

- **EUV lithography**
  - **EUV (Extreme Ultraviolet) lithography** uses an EUV light of the extremely short wavelength of 13.5 nm.
  - It allows exposure of fine circuit patterns with a half-pitch below 20 nm that cannot be exposed by the conventional optical lithography using an ArF excimer laser (193 nm).



- Visible is 400 - 700nm (1.7 to 3eV)
- UV down to about 170 nm (~7eV)
- EUV lithography, it is at ~13.5nm (92eV)

Patterning Racing in Industry

Photolithography (2): Nanolithography

news1 뉴스 KOREA | 포토 | 이슈 | 카드뉴스

정치 | 사회 | 경제 | 산업 | 전국 | 월드 | 문화 | 연예 | 스포츠 | 여행 | TV

과학 | 자동차산업 | 에너지·중공업 | 유통·산업 | 중기·창업 | 패션·뷰티 | 레저 | 호텔·관광 | 의료 | 제약·바이오

홈 > 산업 > 전기전자

[IR]삼성전자 "올 하반기 EUV 적용 7나노 파운드리 본격 양산"

(서울=뉴스1) 주성호 기자 | 2019-01-31 10:31 송고

ASML, 작년 매출 14.6조원…EUV가 효자

ZDNet Korea | 2019.01.24. | 네이버뉴스

삼성·TSMC, **EUV**경쟁 시작…올해 성과 더 기대 (지디넷코리아=양태훈 기자)네덜란드의 반도체 장비업체 ASML이 작년 연간 매출로 109억4천400만유로(약 14조646억원)를 기록했다. 이는 직전년도 대비 매출이 20.89...

TSMC보다 한 발 늦은 **삼성**, 글로벌파운드리 인수로 역전 노리나

뉴스토마토 | 2019.02.27.

세계 반도체 업계에서 7나노 공정에 돌입한 기업은 TSMC와 **삼성**전자뿐이었고, 7나노 공정에 **EUV**장비를 도입한 것은 **삼성**전자가 최초였다. 그동안 반도체 업계에서 웨이퍼에 회로를 새기는 작업에는 불화아르곤(ArF)...

ICT/미디어

삼성 이어 SK하이닉스도 돈다발 들고 찾는 ASML...반도체 미세공정 필수 EUV 뭐길래

조선비즈 박진우 기자

입력 2021.03.04 06:00 | 수정 2021.03.04 07:46

SK하이닉스, 4.7조 들여 EUV 장비 확보

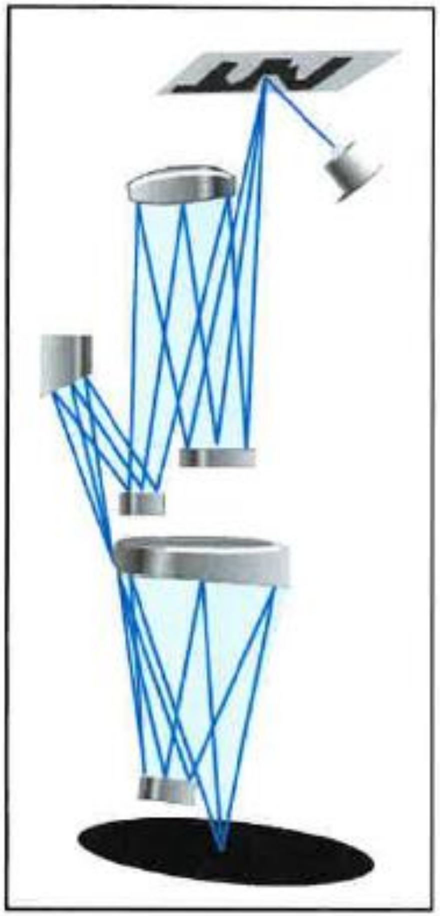
3.5조 투입된 이천 M16 공장보다 1조 비싸

대당 1500억 EUV, M16에 17~18개 들어갈 듯

EUV 유일생산 ASML, D램 확대에 화색

Photolithography (2): Nanolithography

EUV lithography



- First studied by Kinoshita (currently with University of Hyogo) and others from NTT in Japan.

- Almost simultaneously, in the US EUV lithography was beginning to be studied at the Bell Laboratories and continued to be researched at the National Institute in the ’90s.
  => under development since the 1990s when it was called projection X-ray Lithography

- In 1997, the EUV Limited Liability Company (EUVLLC) was established to start extensive research on the EUV lithography.
  => extensive research was started in the US, Europe and Japan.

- Carl Zeiss and ASML have been leading and aggressively working on development of EUV lithography tools.

Comparison

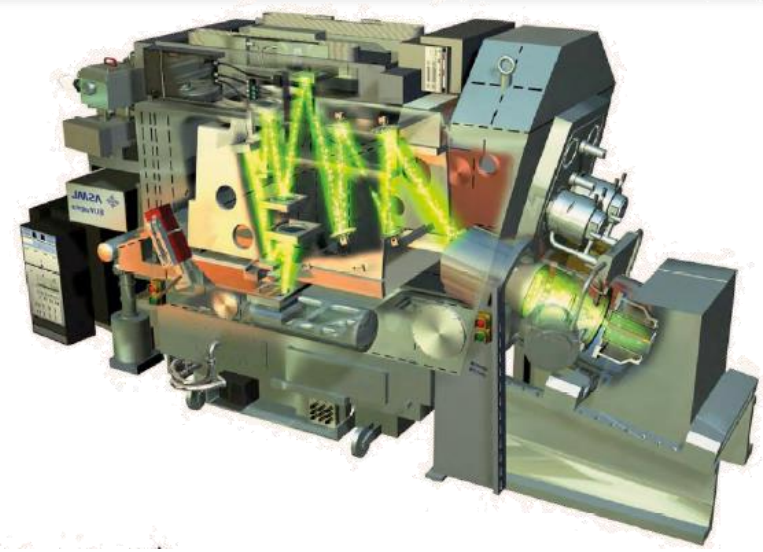
Photolithography (2): Nanolithography

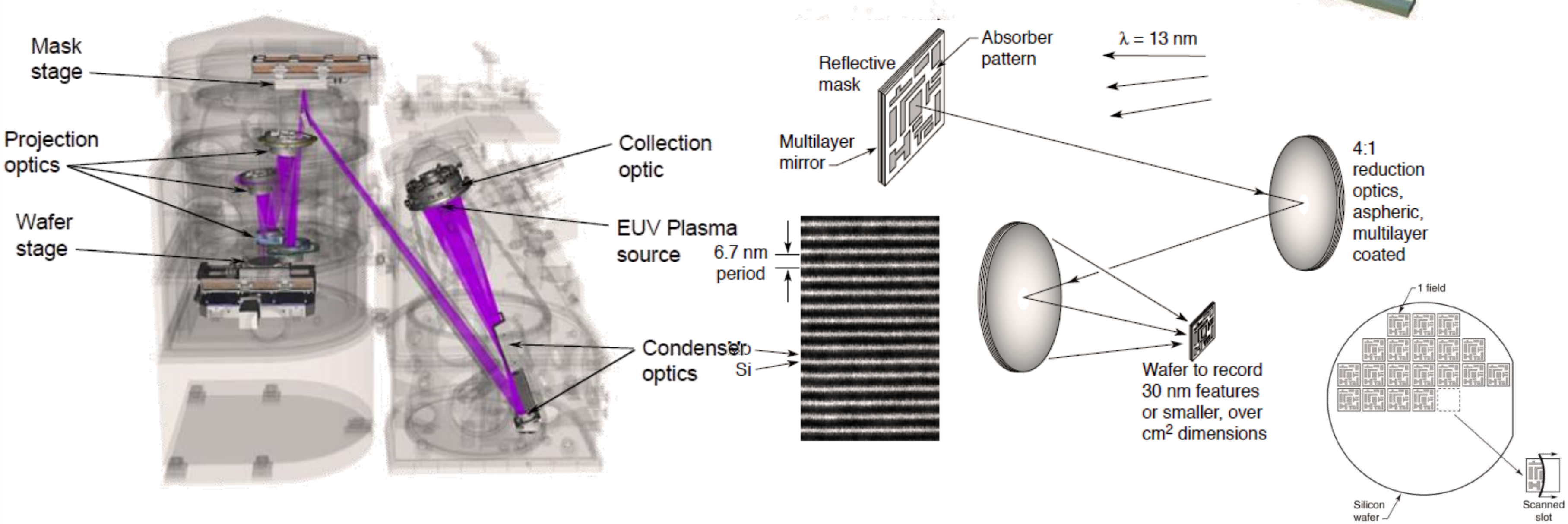
- **DUV (193 nm) vs EUV (13.5 nm)**

ArFi (193nm)	EUV (13.5nm)
Transmission optics (lenses)	Reflection optics (Bragg mirrors)
Excimer laser source	Laser produced plasma source (LPP)
Immersion (NA_{water}=1.33)	Vacuum (NA= 0.33)

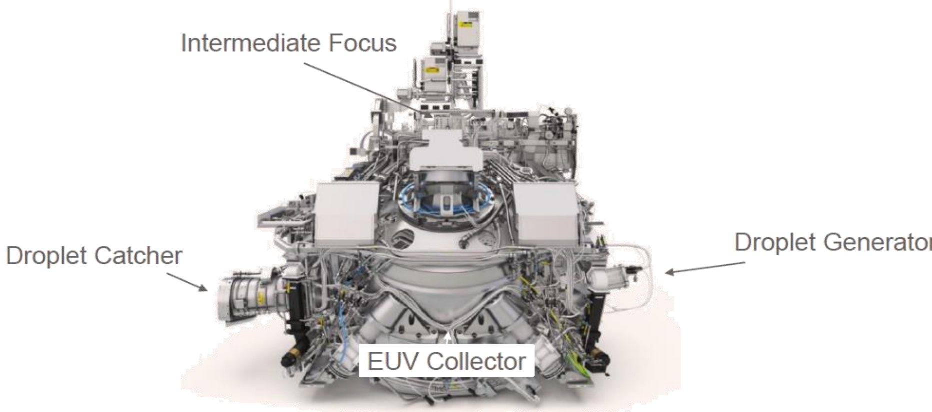
ASML EUV Lithographic System

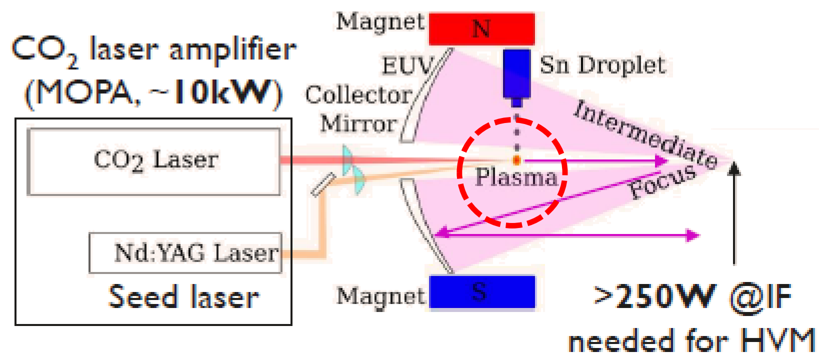
Photolithography (2): Nanolithography

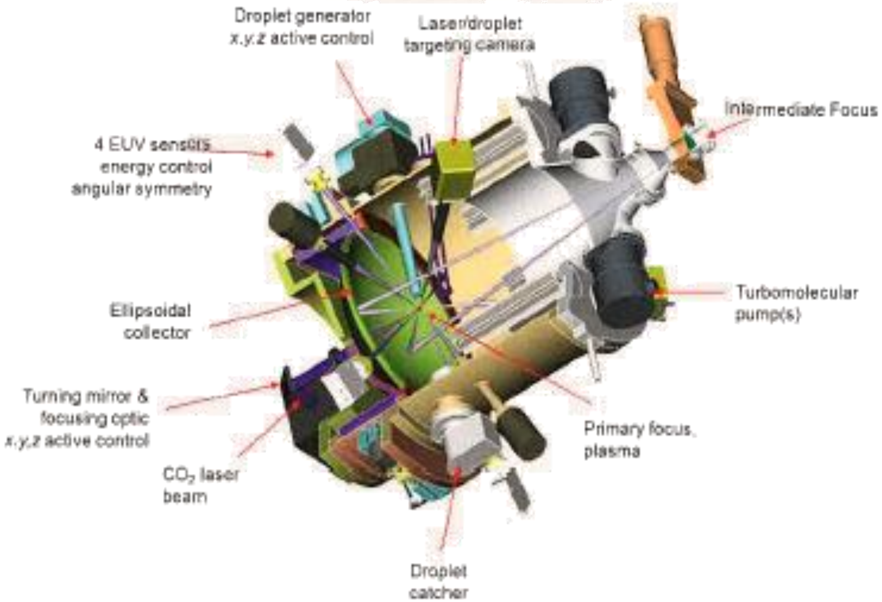




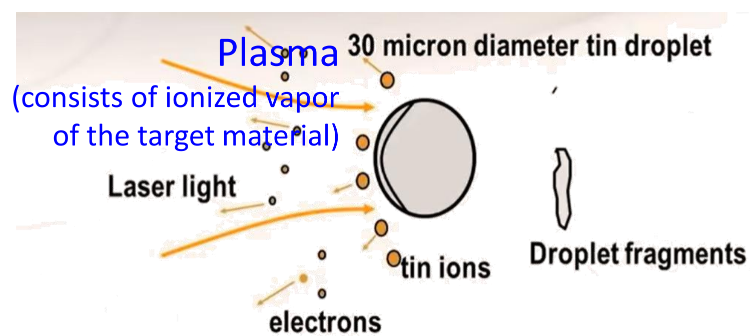
Laser produced plasma (LPP)







- Laser "pre-pulse" flattens the droplet, then the main pulse generates plasma and EUV.



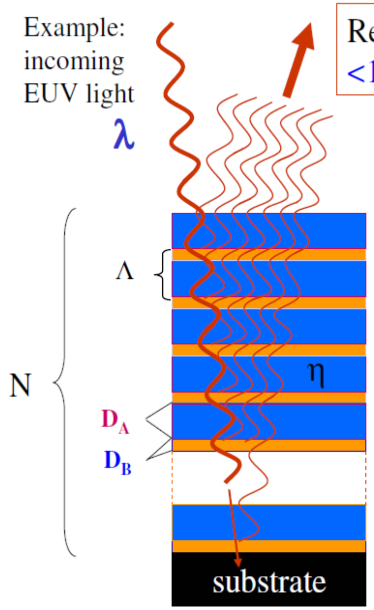
- EUV wavelength from hot dense plasma
  (e^- ion recombination, Sn^{20+})

- **How to generate EUV source (Movie)**

https://www.youtube.com/watch?v=NHSR6AHNiDs

Module 2: Reflective Mask

Reflective mask

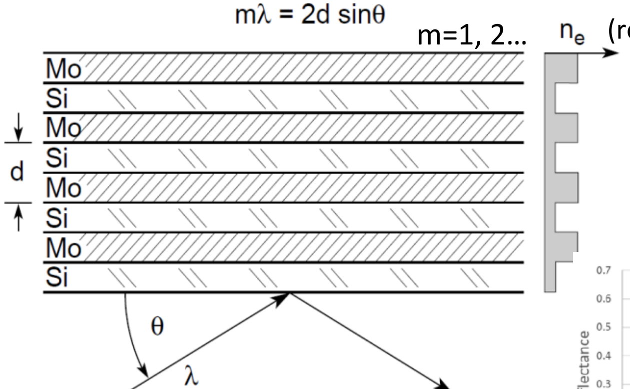


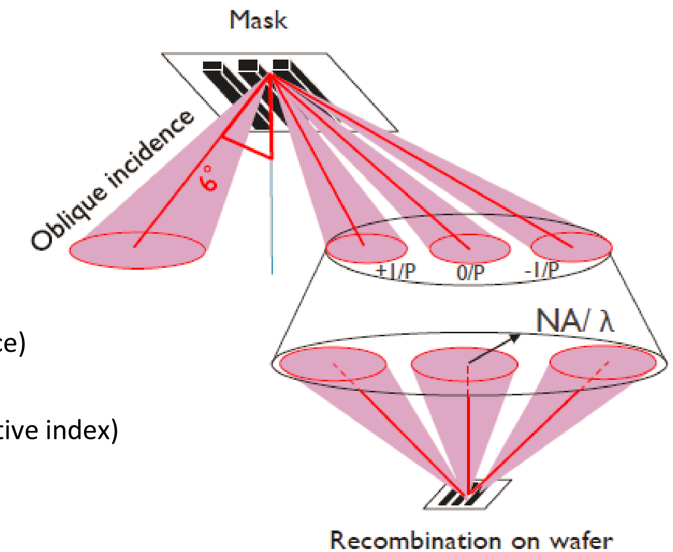
Reflected EUV EM-waves "in phase"
<1% per interface→~70% in total

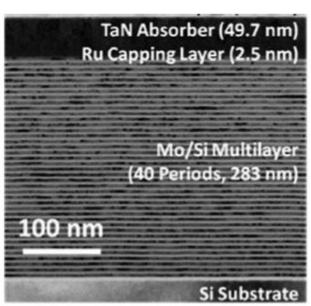
$\Lambda = D_A + D_B$ = bi-layer period
λ = radiation wavelength

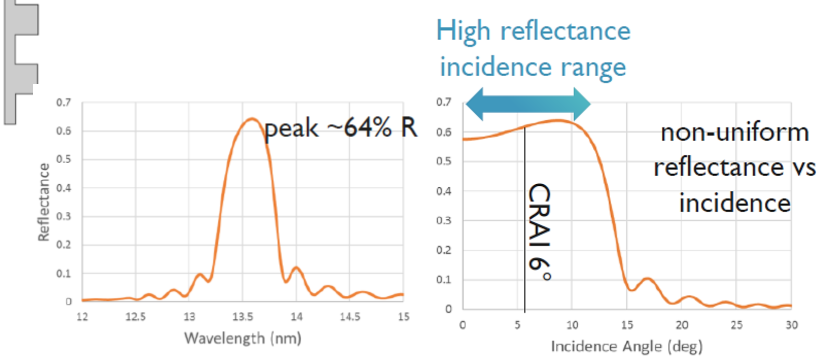
The period $\Lambda \approx$ ½ wavelength (for normal incidence)
Layer thicknesses $\approx$ ¼ wavelength

$m\lambda = 2d \sin\theta$







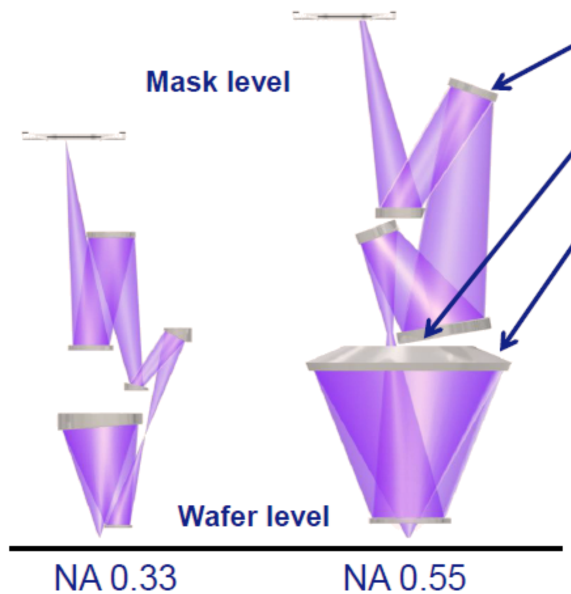


Philipsen V., et al., SPIE, 2013

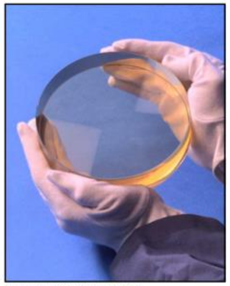
- High reflectivity
- Thermally and environmentally robust multilayers coatings

Module 3: Beam Delivery & Scanning

Photolithography (2): Nanolithography

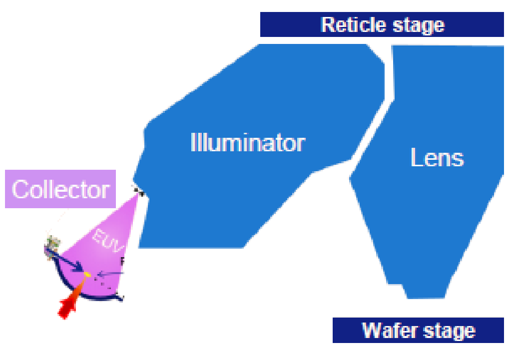


- Extreme aspheres enabling **further improved wavefront / imaging performance**
- Obscuration enables **higher optics Transmission**
- Big last mirror driven by **High-NA**



Tinsley Sample C
Zerodur-M
150 mm diameter

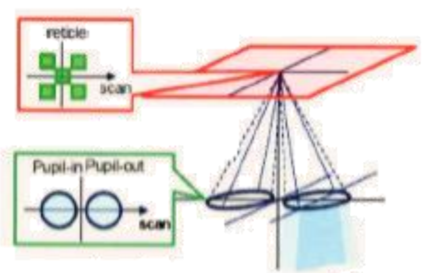
Courtesy of John Taylor, LLNL.



More productivity at constant power through better optical transmission

Current NA

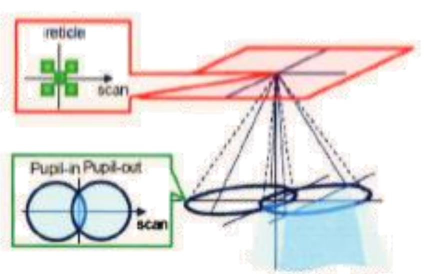
ASML



- Diffraction at 0.33 NA
- 4x Magnification
- Maintaining Chief Ray Angle at mask

High NA

ASML



- Diffraction at 0.5-0.6 NA
- 4x Magnification
- Maintaining Chief Ray Angle at mask not possible

We can not tolerate a higher CRA (shadowing, 3D E&M effects, OPC issues)

Summary

Photolithography (2): Nanolithography