hochschule mannheim

Lithographie-Optiken in der Halbleiterindustrie

Bildquelle: Zeiss SMT GmbH

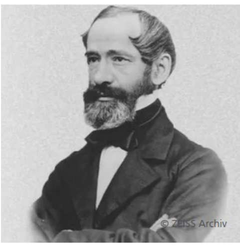
Prof. Dr. Stefan Rist

Fakultät für Wirtschaftsingenieurwesen

Outline

- ZEISS the company
- Development of semiconductor industry and Moores law
- Lithography basics and requirements
- Adjustment of optical systems for lithography
- Necessity of EUV systems
- Outlook

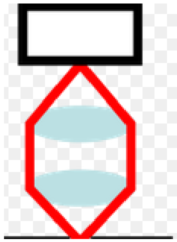
History



- Carl Zeiss, born 1816 founds 1846 his own company in Jena and starts the production of simple optical microscopes on the principle of try and error (pröbeln)

- 1866 collaboration with Ernst Abbe (Prof. in Jena) to find a scientific basis for the production of microscopes, from 1872 all constructions based on Abbes calculations
- 1877 first immersion microscope, till now >30 nobel prize winners using ZEISS microscopes

$$d = \frac{\lambda}{n \sin \alpha}$$



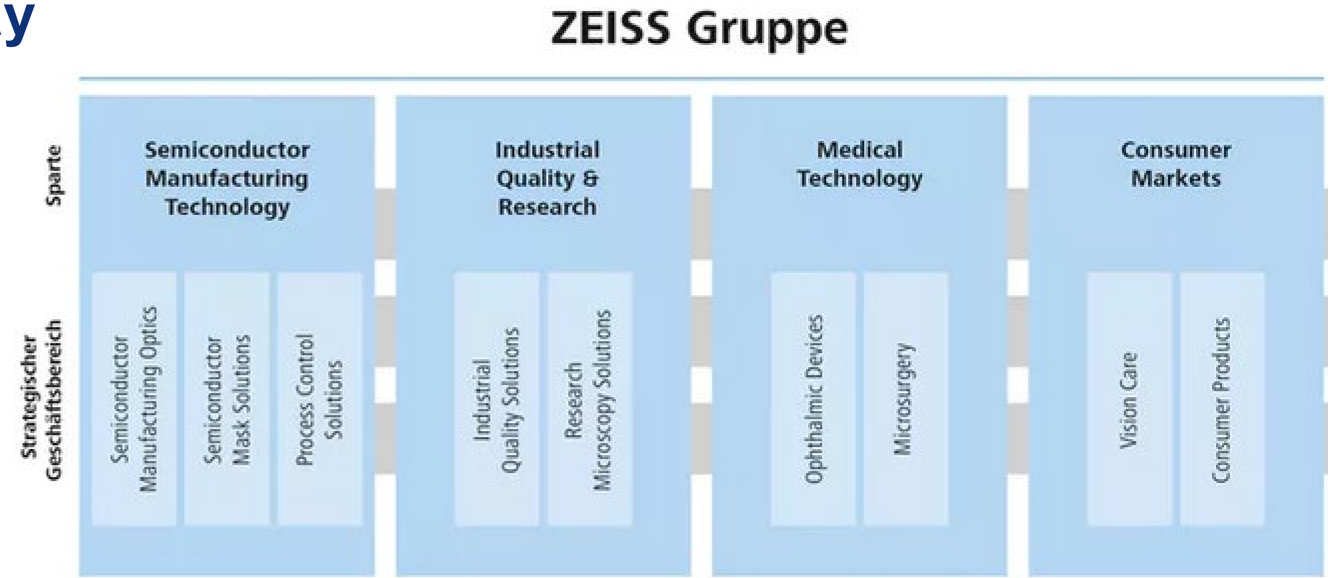
- 1882 collaboration with Otto Schott to produce special optical glases, 1885 foundation of Jenaer Glaswerk (today Schott AG)
- 1888 death of Carl Zeiss and creation of the Carl Zeiss foundation 1889 by Ernst Abbe which becomes single shareholder of both companys

ZEISS today

ZEISS Gruppe

	Semiconductor Manufacturing Technology	Industrial Quality & Research	Medical Technology	Consumer Markets
Sparte	Semiconductor Manufacturing Technology	Industrial Quality & Research	Medical Technology	Consumer Markets
Strategischer Geschäftsbereich	Semiconductor Manufacturing Optics; Semiconductor Mask Solutions; Process Control Solutions	Industrial Quality Solutions; Research Microscopy Solutions	Ophthalmic Devices; Microsurgery	Vision Care; Consumer Products

ZEISS today



turnover (mio)	1500	1500	1500	1100
employees	3400	6800	4900	10500

ZEISS total: ~ 29000 employees,
~ 5800M turnover
~ 535M net profit in 2018

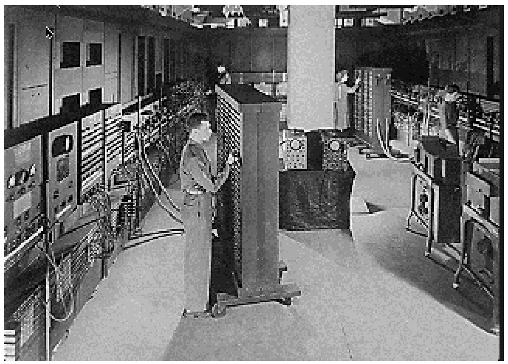
ZEISS today (ownership)

oldest private foundation with the aim to promote science and technology in germany

„Laptop-Transport“, Norwich 1957: Britain's First Municipal Computer

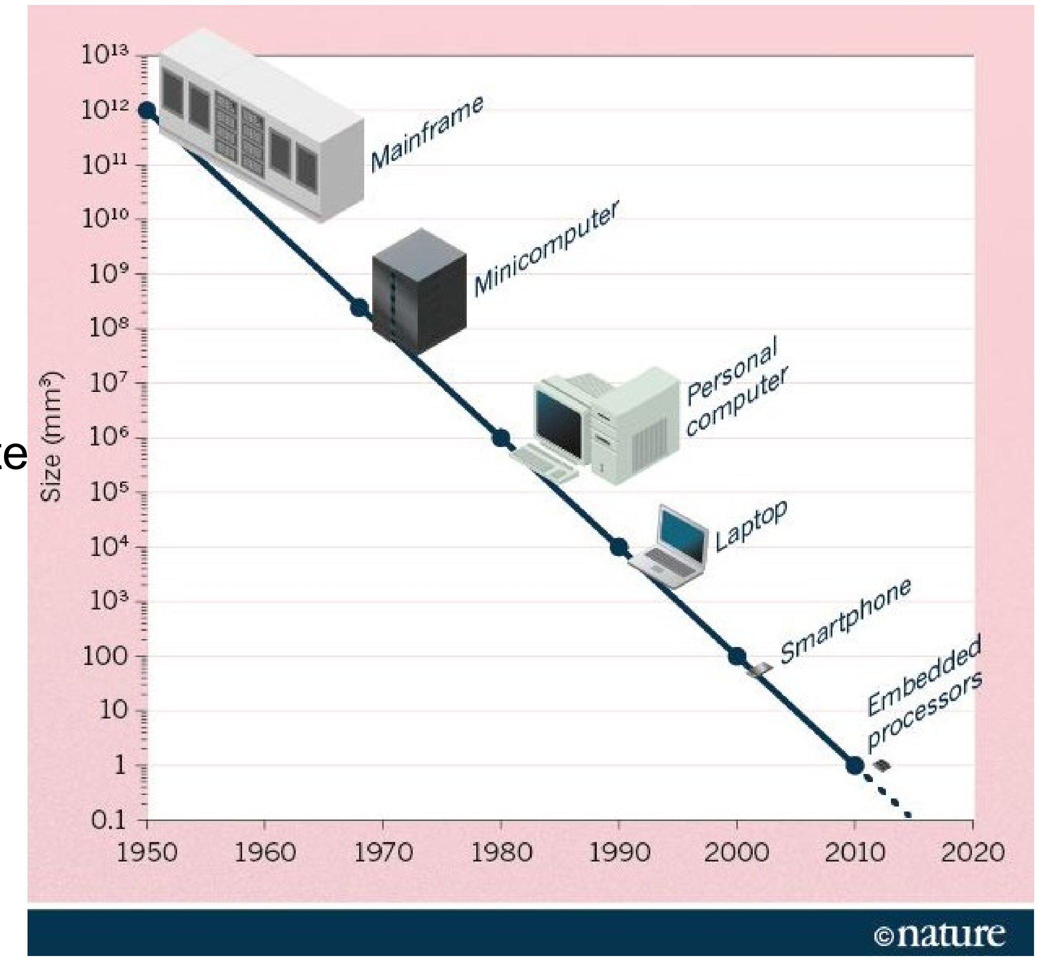
THM
TECHNISCHE HOCHSCHULE MITTELHESSEN
Dr. A. Christidis • WS 2017 /18

Computer history

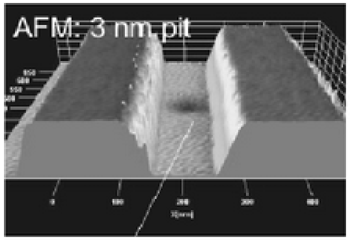


speed: ~0.1 MIPS, memory: ~32Kbyte
prize (today): ~ 7 mio $

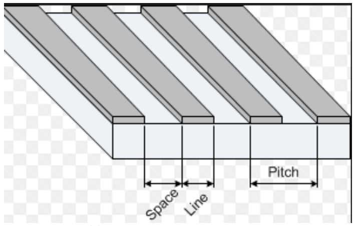
speed: ~4x1000 MIPS,
memory: ~1Gbyte



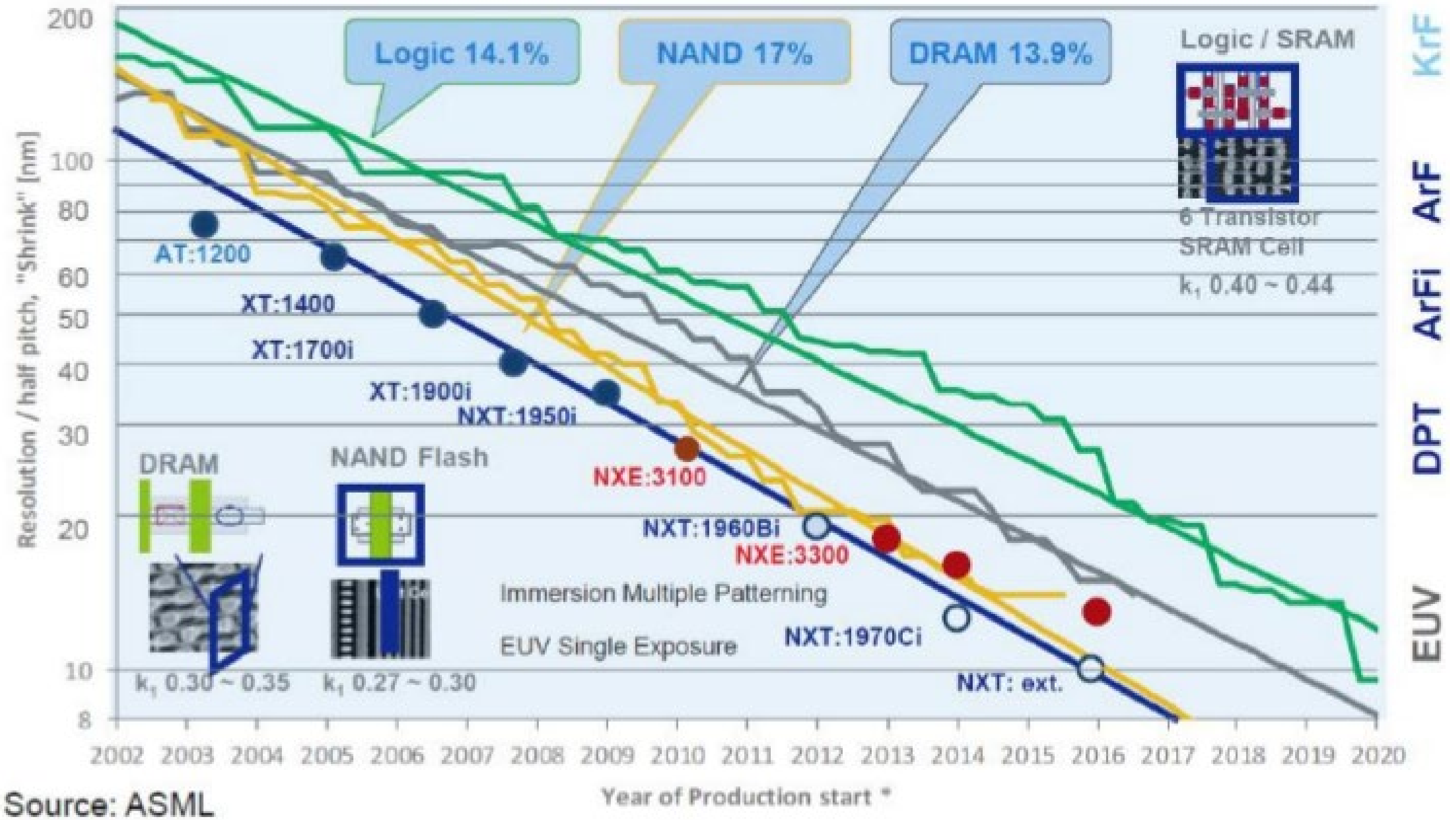
Moores law:



Hellweg et. al (ZEISS)



https://www.halbleiter.org



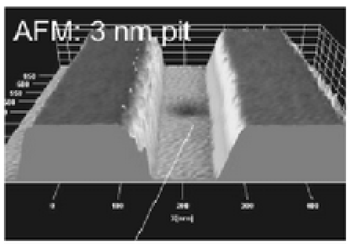
Source: ASML

Gordon Moore, Cofounder of Intel (1965):

Number of transistors per area doubles every 24 month

Exponential improvement for more than 50 years!

Moores law:



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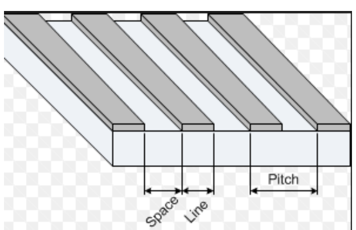
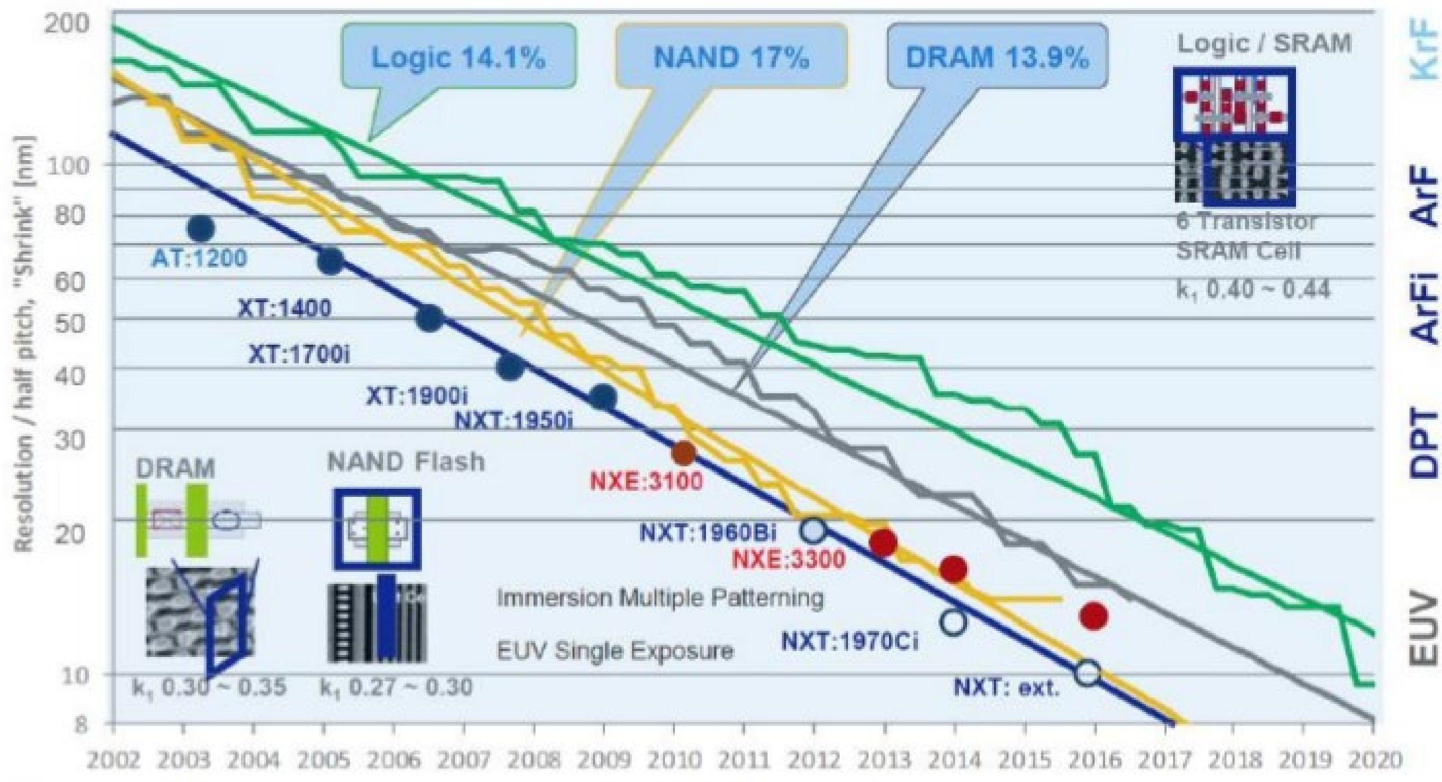


https://www.halbleiter.org



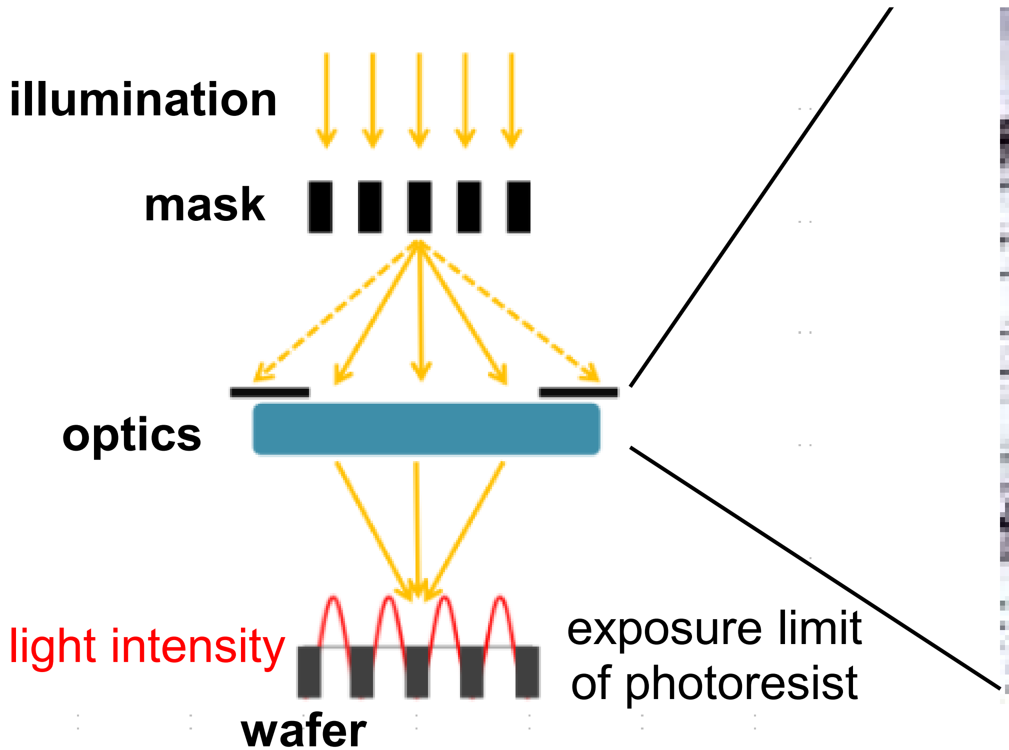
Source: ASML

Gordon Moore:

If the car industry advanced as rapidly as the semiconductor industry, a Rolls Royce would get half a million miles per gallon, and it would be cheaper to throw it away than to park it.

Basic principle of lithography

principle of pattern formation on the wafer in lithography



optics in produktion @ ZEISS

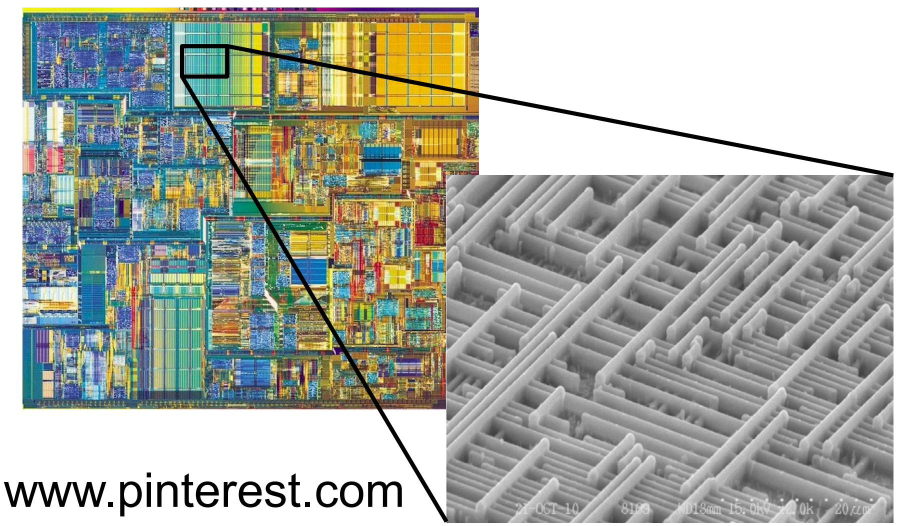
resolution 38nm: ~ 160 Si atoms

ASML scanner with ZEISS optics

www.asml.com/

Building 3D structures and resulting challenges

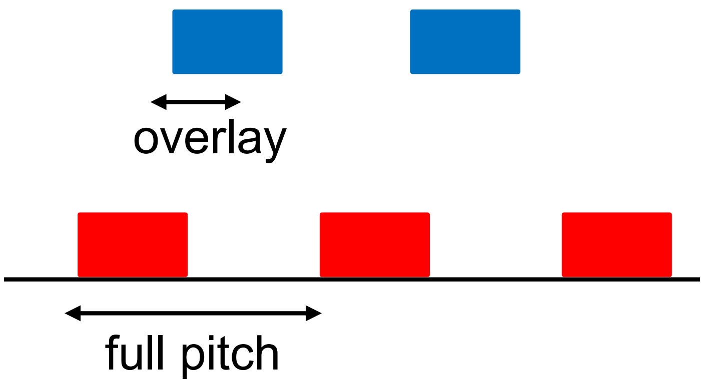
Intel pentium processor:



www.pinterest.com

https://www.ial-fa.com/

A microchip consists of several layers of circuits on top of each other



Each layer has to be placed on top of the others with an accuracy of the order of ~10 Si atoms!

Today: Half pitch <20nm
overlay: few nanometers
1nm ~ 4Si atoms!

Making of a lens for a lithography system

production of all optical elements with sub nm accuracy (5nm growth of human hair/s)

scale ca. 1~100

https://www.nijboerzernike.nl/_html/SCI.htm

mechanical alignment of floors:
- **hight accuracy: ~0.5mm**
- **vertical accuracy:**
  width of human hair[50µm]

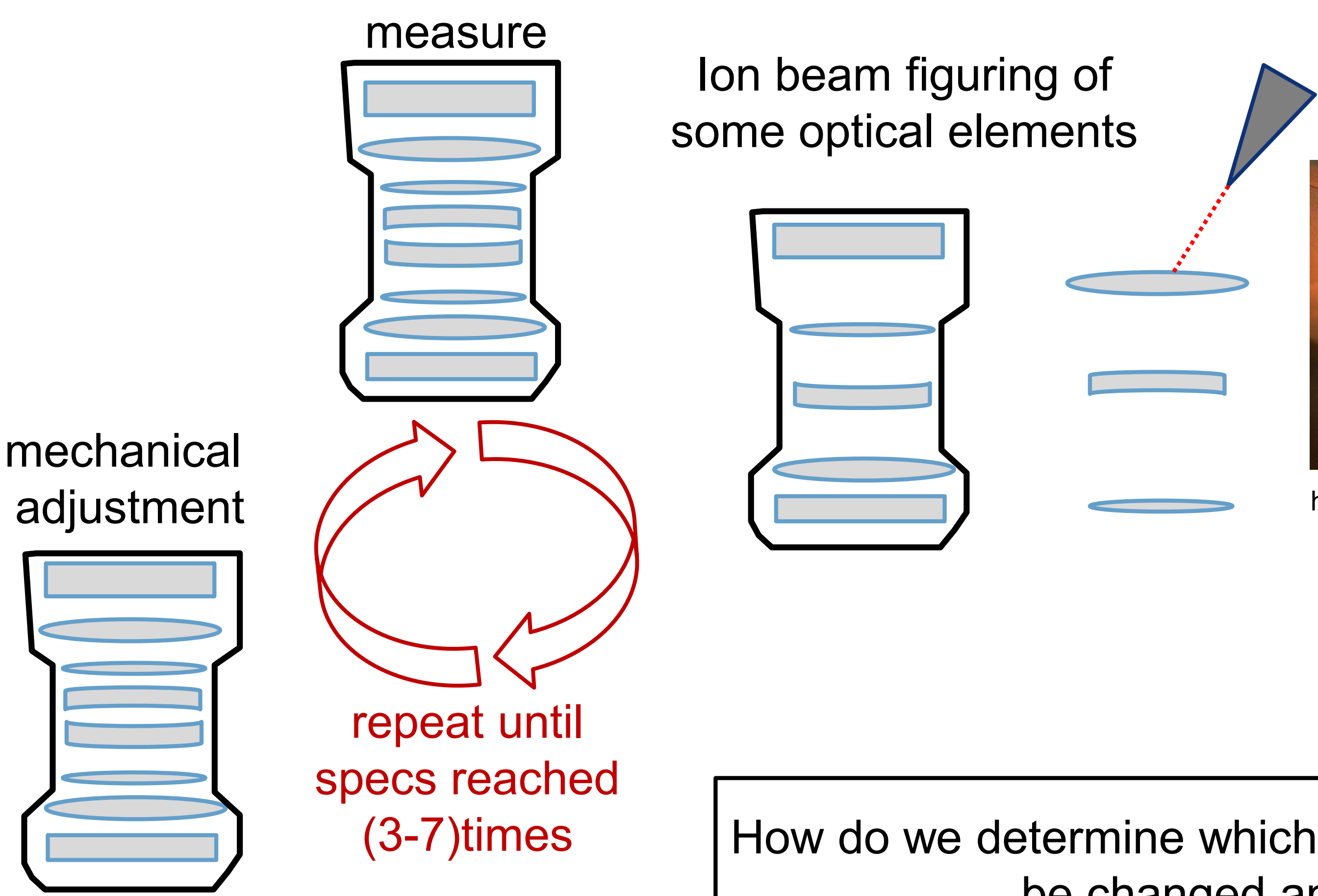
⇨ **way out of specification**

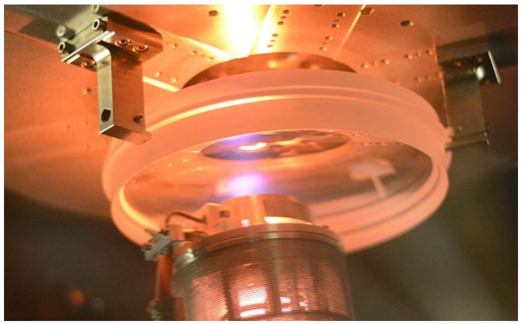
several lens elements equiped with piezo-mechanical actuators total of ~ 100 DOF

⇨ **still not good enough**

https://www.yumpu.com/en/document/read/5933051/optics-for-euv-lithography-sematech

Adjustment process @ Oberkochen



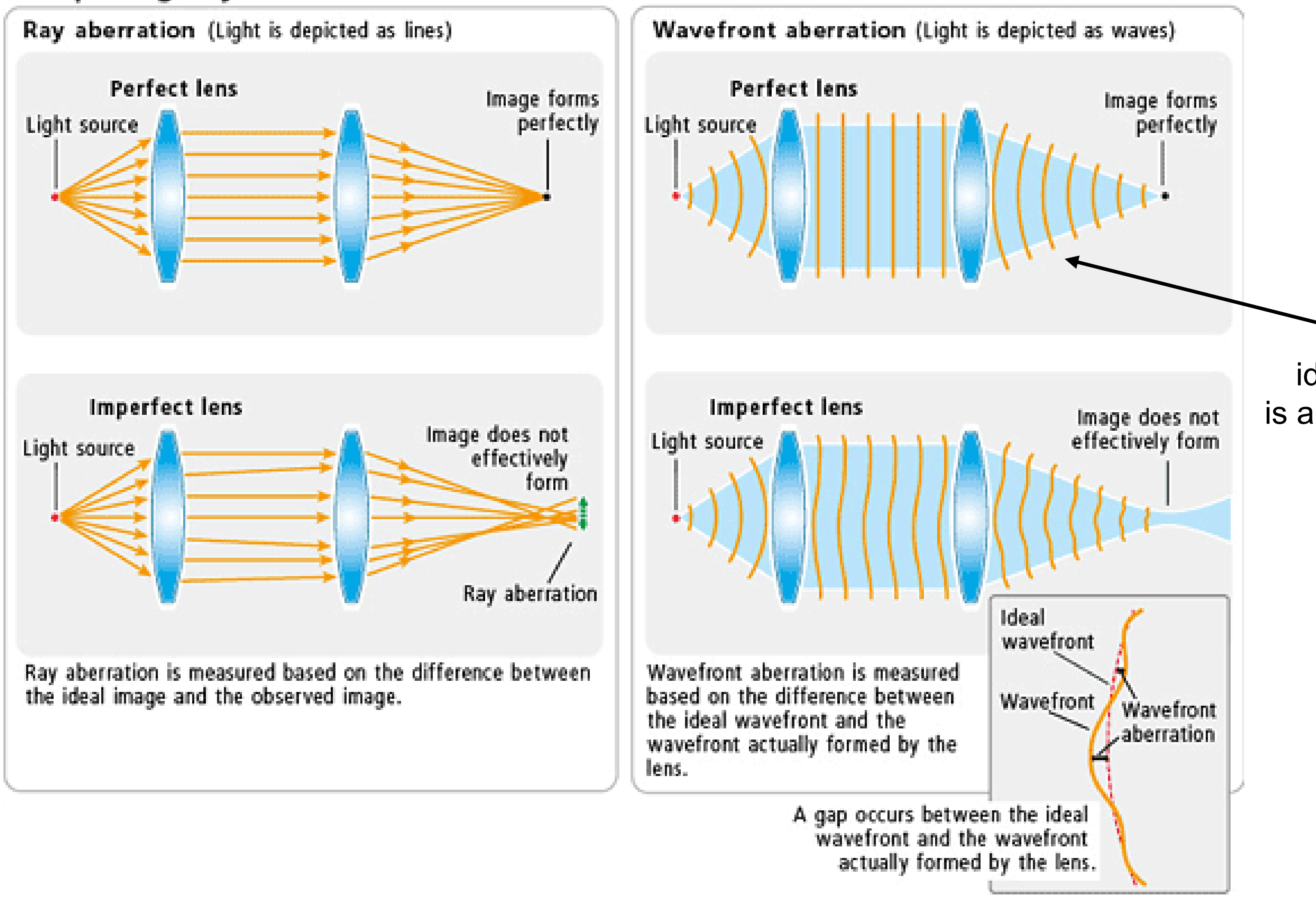


https://www.opteg.com/ion-beam-figuring

max error <50pm
½ Si - atom

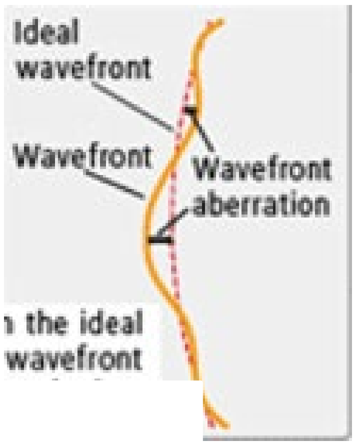
How do we determine which lens elements should be changed and how?

Comparing ray aberration and wavefront aberration



ideal wavefront
is a spherical wave!

Adjustment as an optimization problem

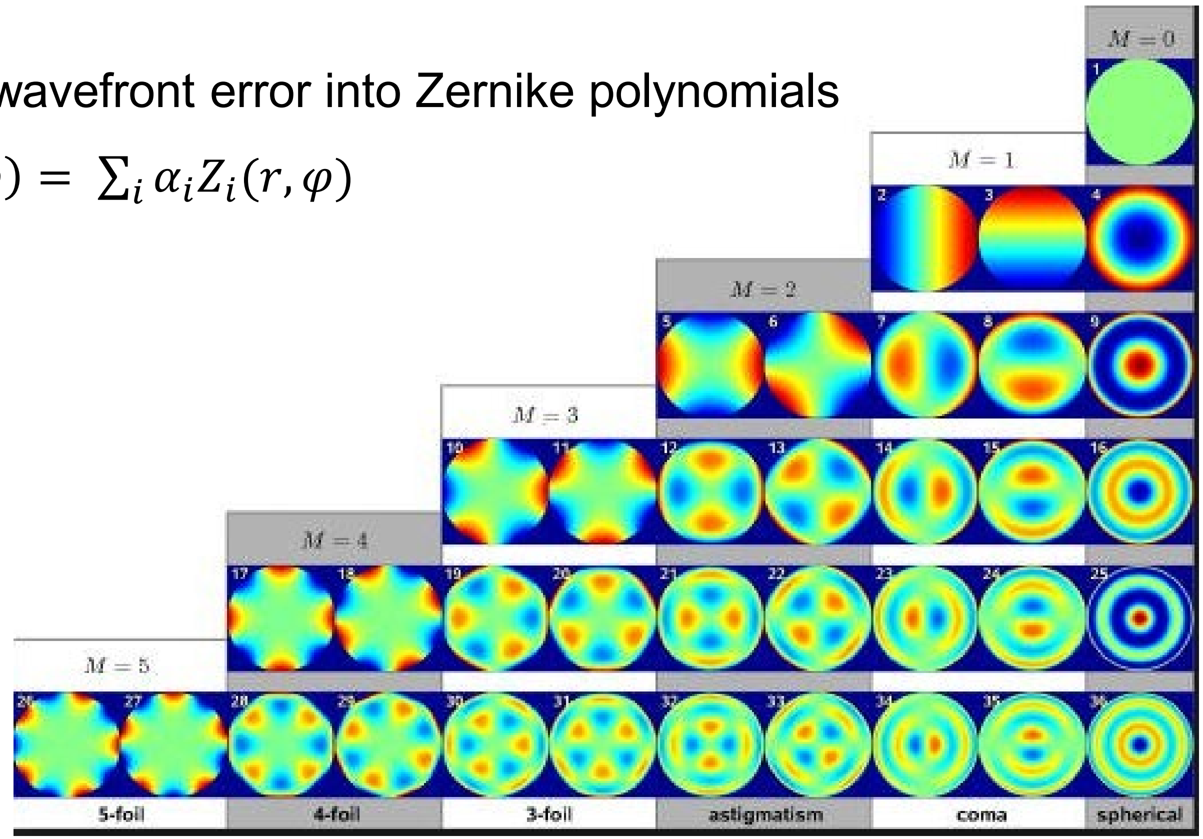


$$W(r,\varphi) = W_{ideal}(r,\varphi) + W_{ab}(r,\varphi)$$

Goal: $W_{ab}(r,\varphi) \rightarrow 0$

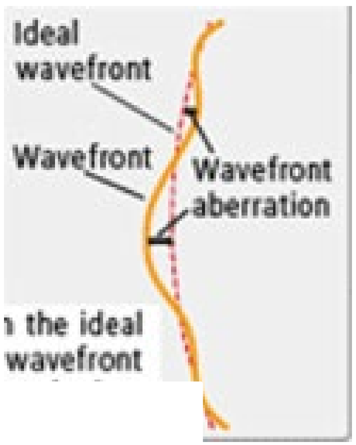
expand wavefront error into Zernike polynomials

$$W_{ab}(r,\varphi) = \sum_i \alpha_i Z_i(r,\varphi)$$



https://www.spiedigitallibrary.org

Adjustment as an optimization problem



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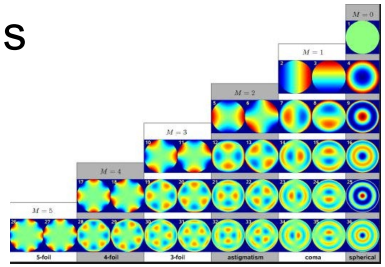
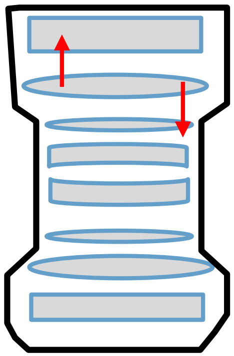


$$W_{ab}(r,\varphi) = \sum_i \alpha_i Z_i(r,\varphi)$$

Aberration vektor in Zernike Basis:



$$\vec{W}_{ab} = \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \end{pmatrix}$$

$$\vec{a} = a_x\hat{e}_x + a_y\hat{e}_y + a_z\hat{e}_z = \sum_i a_i\hat{e}_i$$

manipulating the lens we can change the aberrations:

$$\delta\vec{W} = M \cdot \delta\vec{x}$$

change in wavefront

sensitivity matrix

manipulator movement

https://www.spiedigitallibrary.org

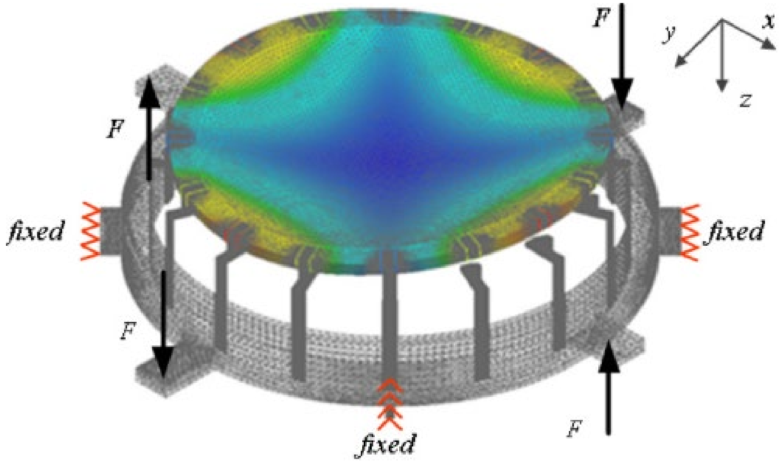
Adjustment as an optimization problem

What we want: $$W_{ab} + M \cdot \delta x = 0$$

measured aberrations — adjustment

used manipulators:

- piezo mechanical elements:
- controlled deformations:
- Ion beam figuring of lens surfaces:
- spatially resolved temperature changes:



osa.publishing.org

total of ~5000 DOF for δx and >10000 optical spezifications

[100 Zernike coeficients
65 fieldpoints
Zernike combinations]

Adjustment as an optimization problem

What we want: $W_{ab} + M \cdot \delta x = 0$

measured aberrations — adjustment

⇒ Exakt solution impossible!

$$||W_{ab} + M \cdot \delta x|| \rightarrow min$$

use a smart norm!
otherwise the best mathematical solution may be impossible to manufacture!

S. Rist: (DE102015206448A1; EP3079016A2; US20160299436A1)

used manipulators:

- piezo mechanical elements:
- controlled deformations:
- Ion beam figuring of lens surfaces:
- spatially resolved temperature changes:

total of ~5000 DOF for δx and >10000 optical spezifications [100 Zernike coeficients, 65 fieldpoints, Zernike combinations]

Necessity of EUV

$$d = k \cdot \frac{\lambda}{NA}$$

Deep Ultraviolet numbers:

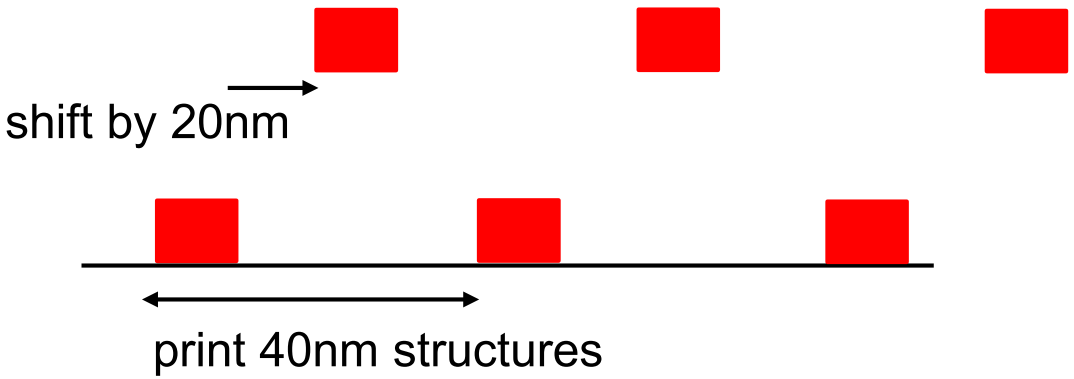
$$k > 0.25$$

$$\lambda = 193nm$$

$$NA = 1.35$$

$$d > 0.25 \cdot \frac{193nm}{1.35} = 36nm$$

How to make 20nm resolution structures?



double patterning:

- very expensive
- difficult to impossible for complex structures
- no further improvement possible

⇨ **decrease λ !**

Change to EUV

$$\lambda = 193nm \rightarrow \quad \lambda = 13.5nm$$

EUV light is absorbed by everything

- complete system in vacuum
- only mirrors instead of lenses
- no laser for EUV light available

What do they have in common with EUV technology?

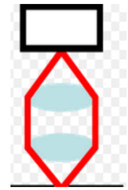
sometimes evolution makes a jump…

https://observer.com/2018/06/disney-fox-comcast-x-men-marvel-info-details/

Change to EUV

Evolution of lenses @Zeiss

$$d = \frac{\lambda}{n \sin \alpha}$$



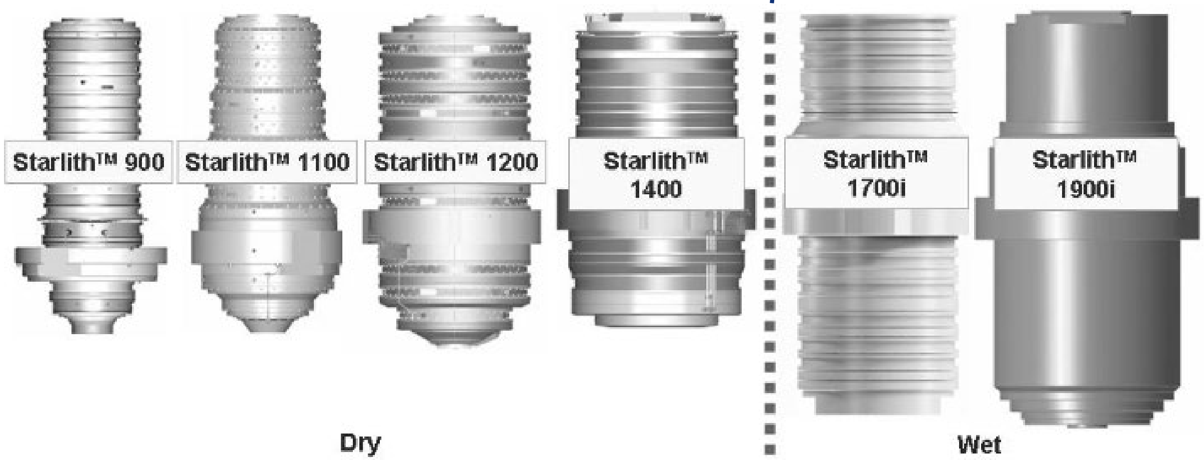
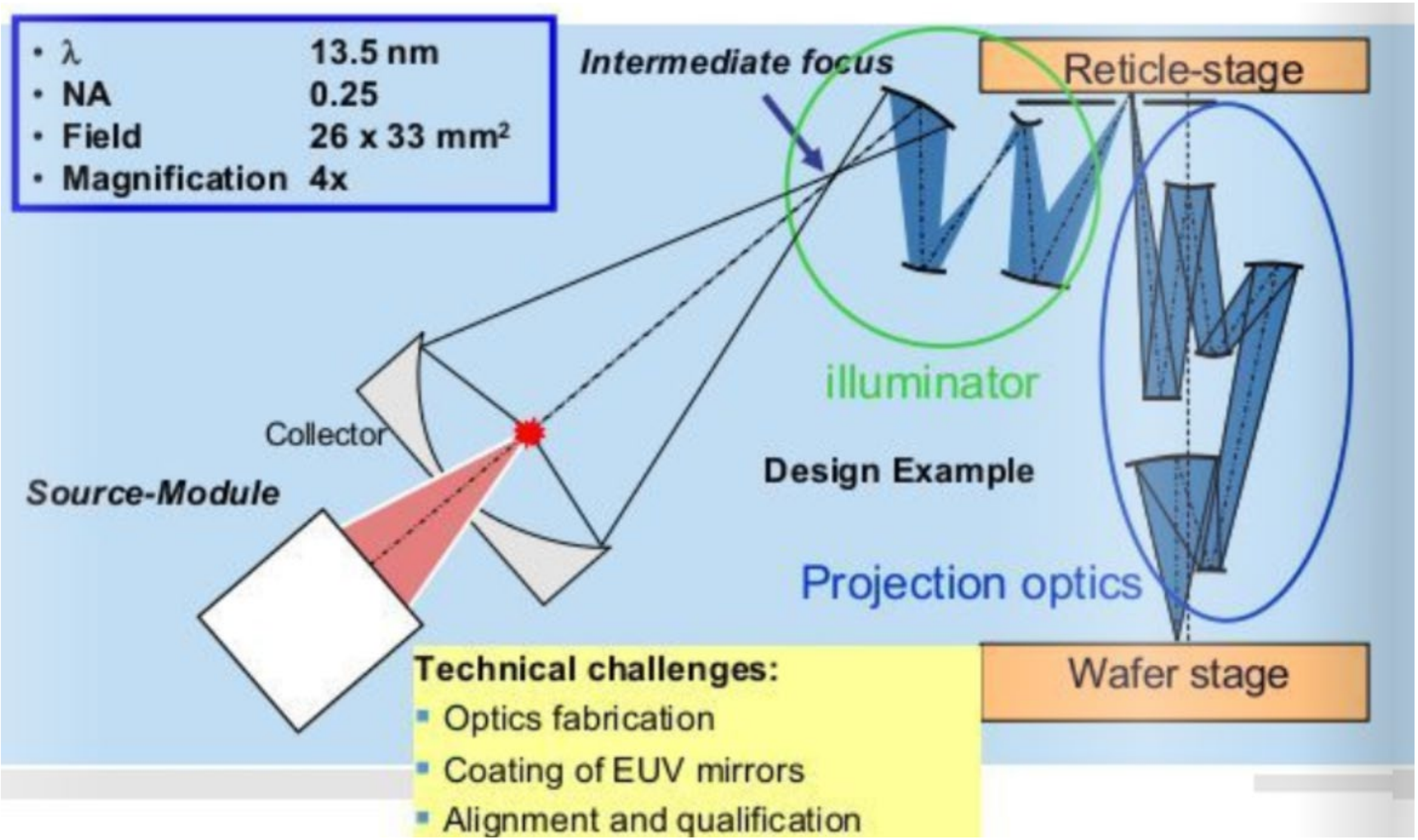


Figure 16. 193nm lens evolution at Carl Zeiss

http://www.narrowbandimaging.com/incoming/Optical_lithography_40_years_and_holding_Bruning_2007.pdf

https://www.electrooptics.com/feature/euv-lithography-reaches-starting-line

EUV optics schematic

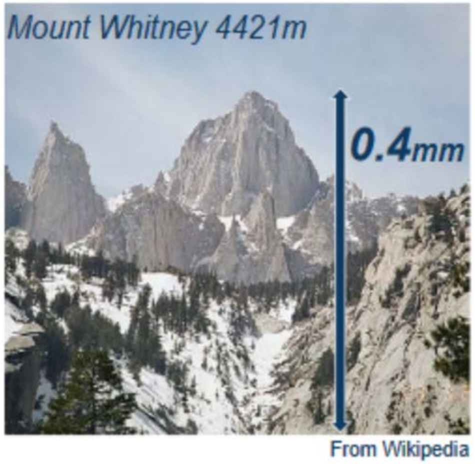


https://www.yumpu.com/en/document/read/8446415/optics-for-euv-lithography-sematech

EUV mirror quality

Mirrors: <50pm rms surface roughness

Inflated to the size of the contiguous United States...

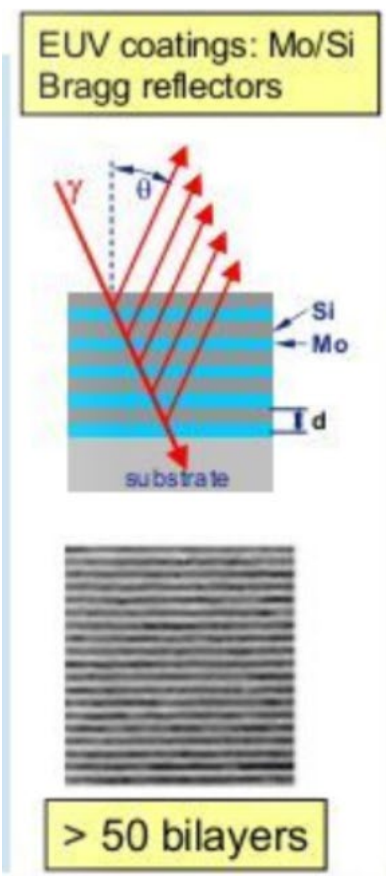


...roughness defects must not be taller than 0.4mm.

https://www.euvlitho.com/2018/P22.pdf

hochschule mannheim

Highly specialized coating technology

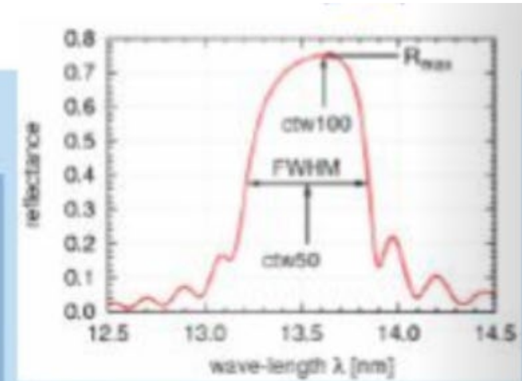


Challenges

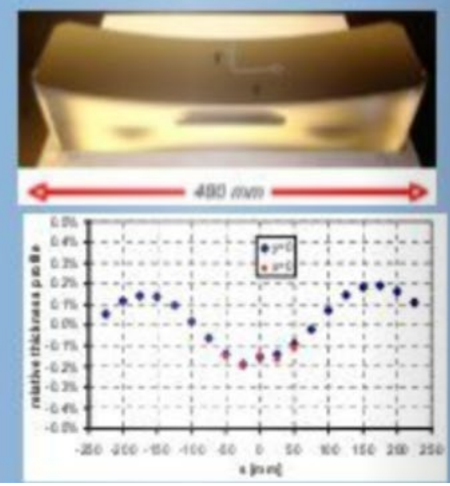
- high peak reflectance and large FWHM
- wave-length matching requires a few ‰ control of absolute thickness
- lateral uniformity of a few ‰ for d
- film stress less than ~ 50 MPa
- thermal stability of several 100°C

total coating stack non correctable thickness error <30pm rms

Enabling the Nano-Age World®



State of the art profile control on an EUV illuminator mirror

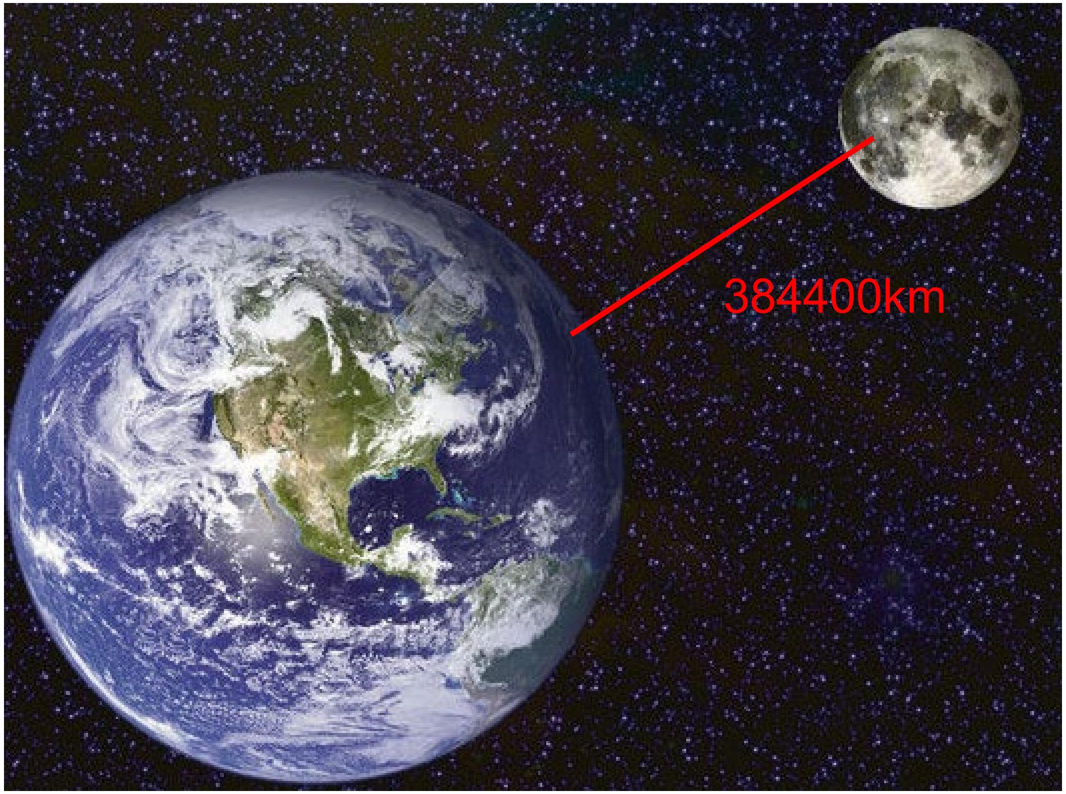


https://www.yumpu.com/en/document/read/8446415/optics-for-euv-lithography-sematech

EUV mirror dynamic control stability

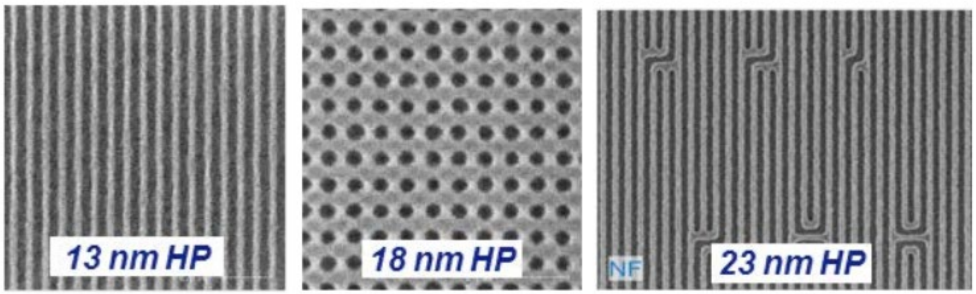
EUV mirrors have placing acurray <0.1nm

one could stabilize a laserspot on the moon within 10cm accuracy from earth



https://austria-forum.org

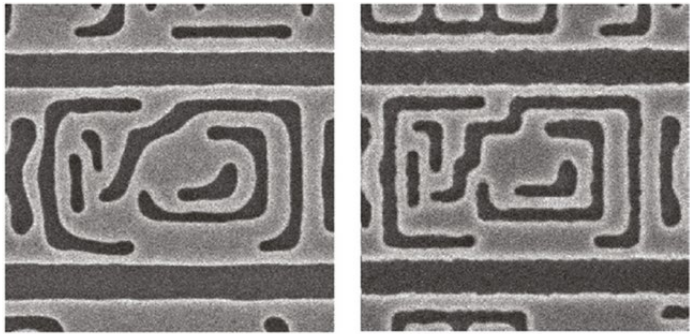
Performance



Source: ASML

https://www.euvlitho.com/2018/P22.pdf

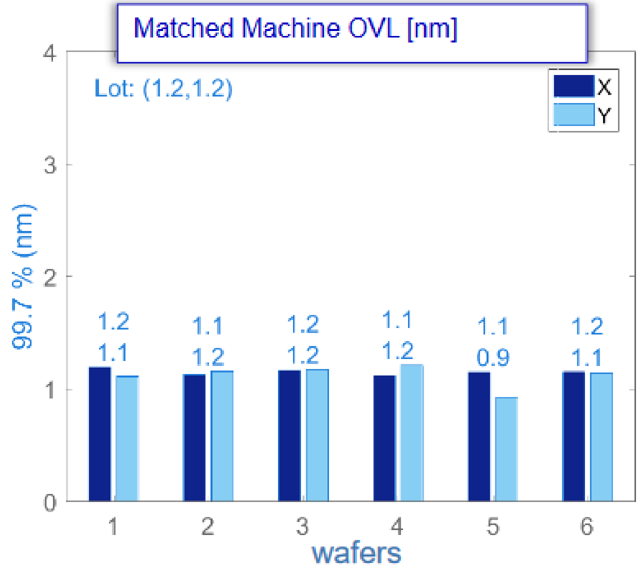
24nm structures for 10nm logical node



tripple patterning 193nm

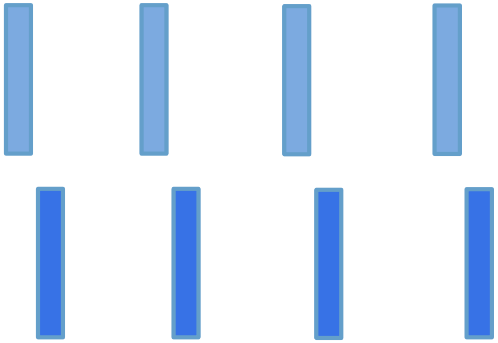
single exposure EUV

https://www.degruyter.com/view/j/aot.2017.6.issue-3-4/aot-2017-0040/aot-2017-0040.xml



https://www.euvlitho.com/2018/P22.pdf

machine to machine overlay 1.2nm
~5 Si atoms



DUV scanner versus EUV scanner

193nm

13.5 nm

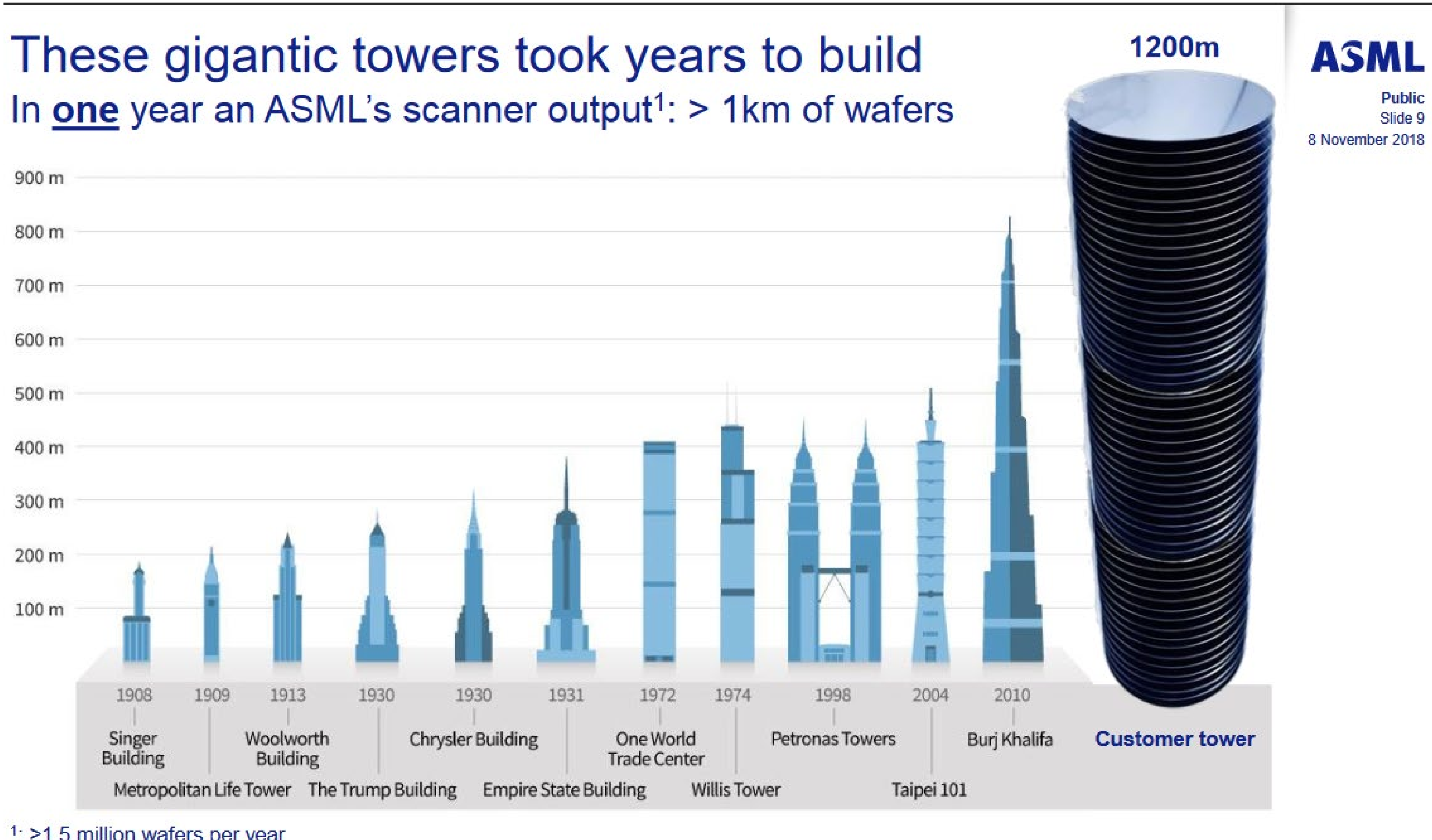
how is this possible?

price ~ 60 Mio Euro

price ~ 120 Mio Euro

www.asml.com

Productivity (DUV)

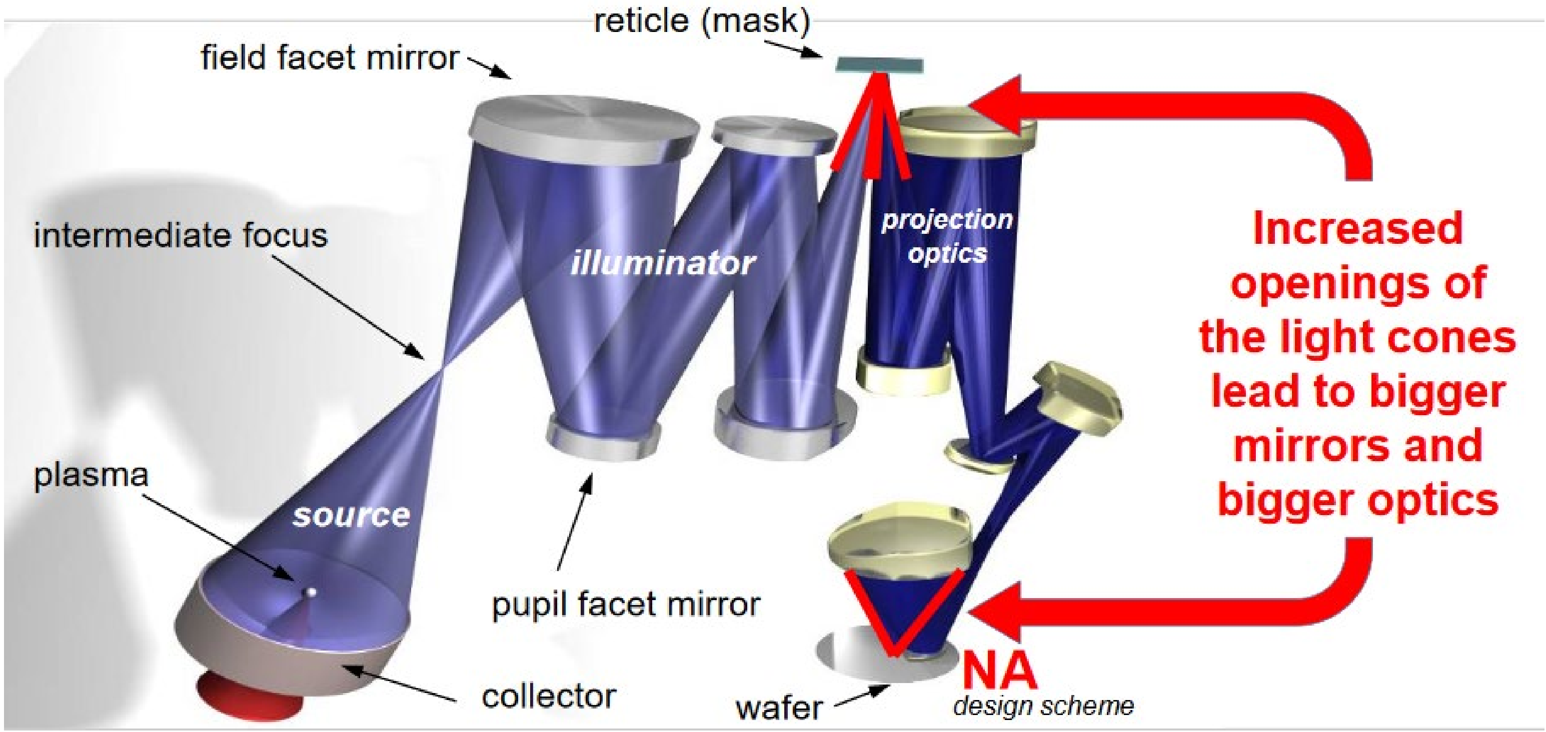


https://www.euvlitho.com/2018/P22.pdf

Outlook

$$d = k \cdot \frac{\lambda}{NA}$$

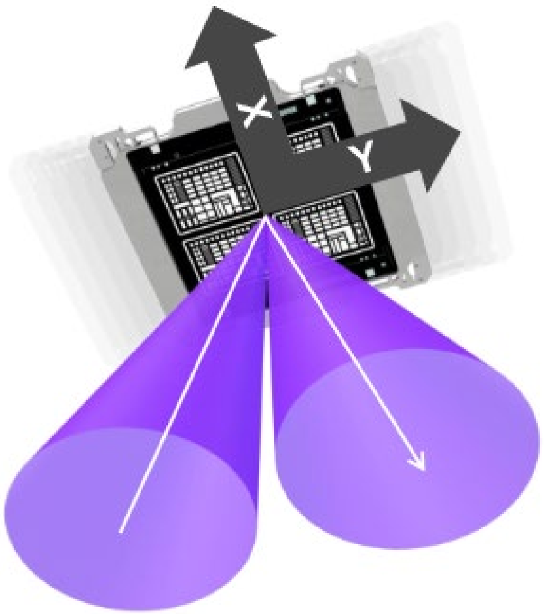
go to high NA



https://www.euvlitho.com/2018/P22.pdf

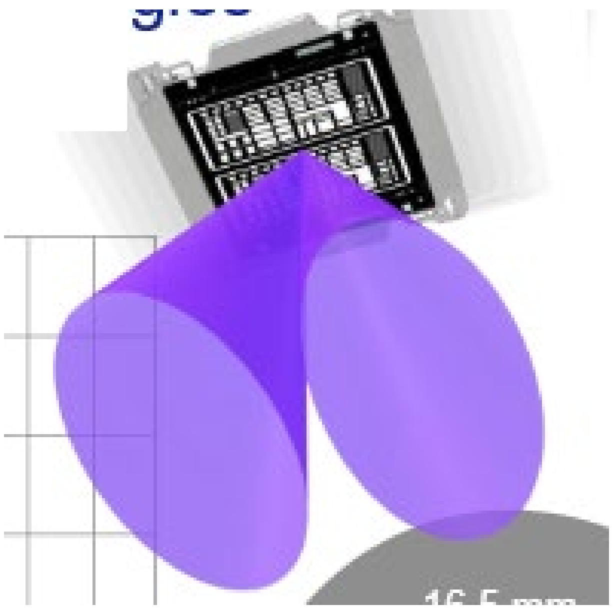
Anarmorphic optics

NA = 0.33



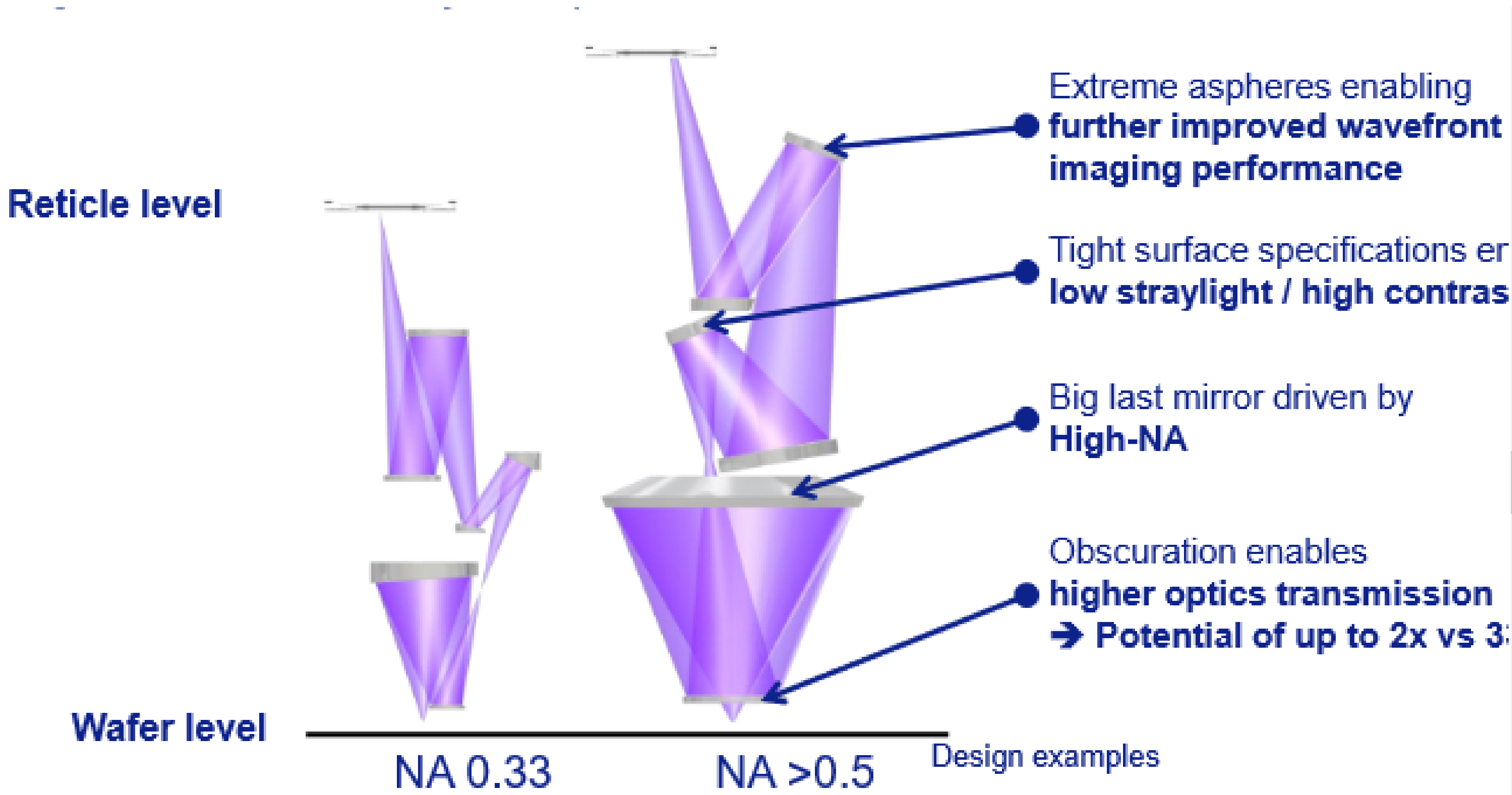
MagX: 4x
MagY: 4x

NA >0.5



MagX: 4x
MagY: 8x

Comparison of design examples



https://hobbydocbox.com/Photography/69004093-High-na-euv-lithography-enabling-moore-s-law-in-the-next-decade.html

Carl Zeiss SMT site

Construction status

October 2017

https://www.euvlitho.com/2018/P22.pdf

ZEISS

https://www.zeiss.de