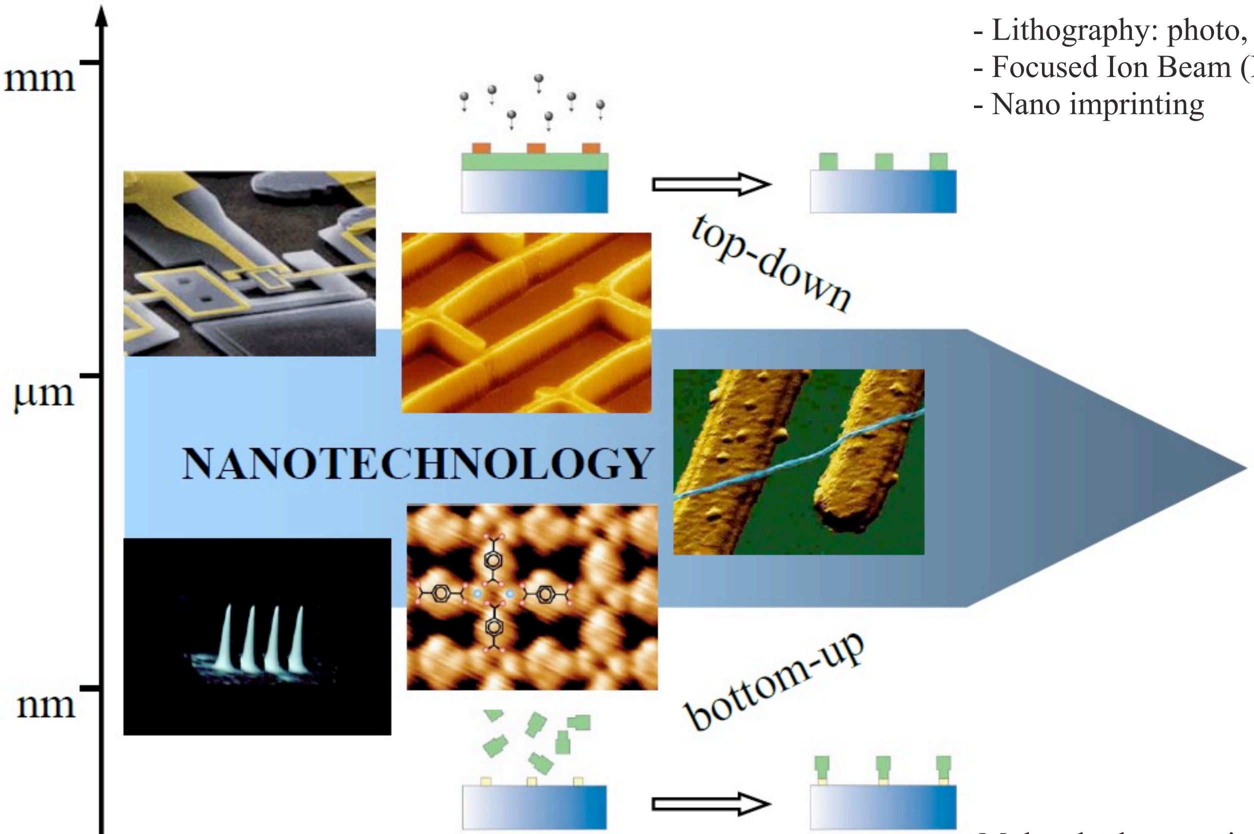
How to make the nanostructures: two approaches

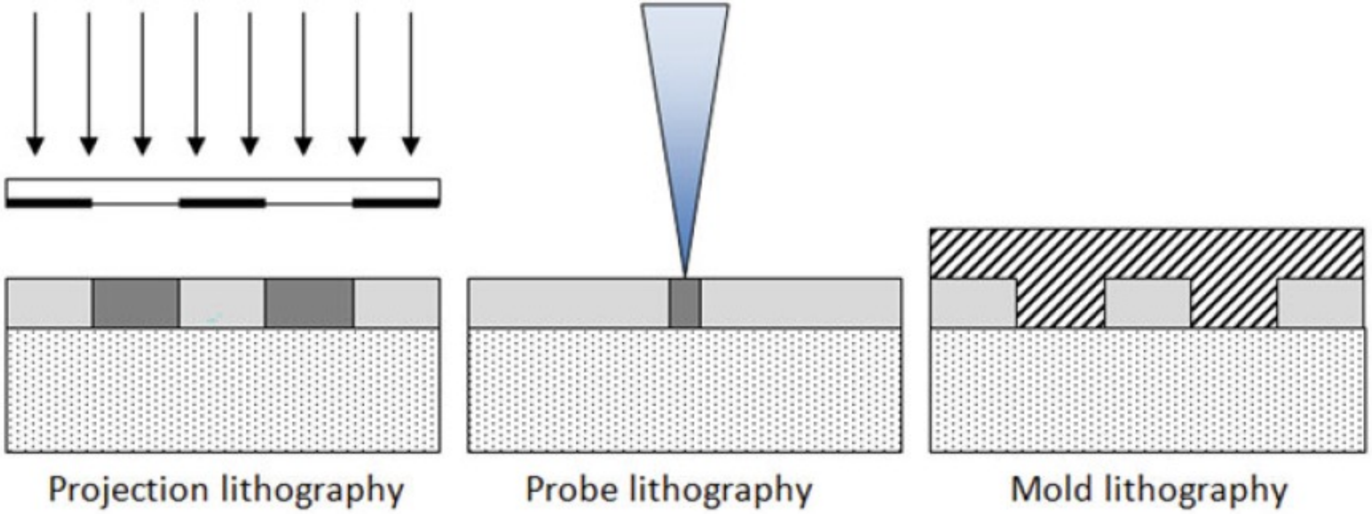
- Lithography: photo, UV, e-beam
- Focused Ion Beam (FIB)
- Nano imprinting



- Molecular beam epitaxy (MBE)
- Self assembly
- Chemical vapor deposition (CVD)
- Atomic manipulation (STM)

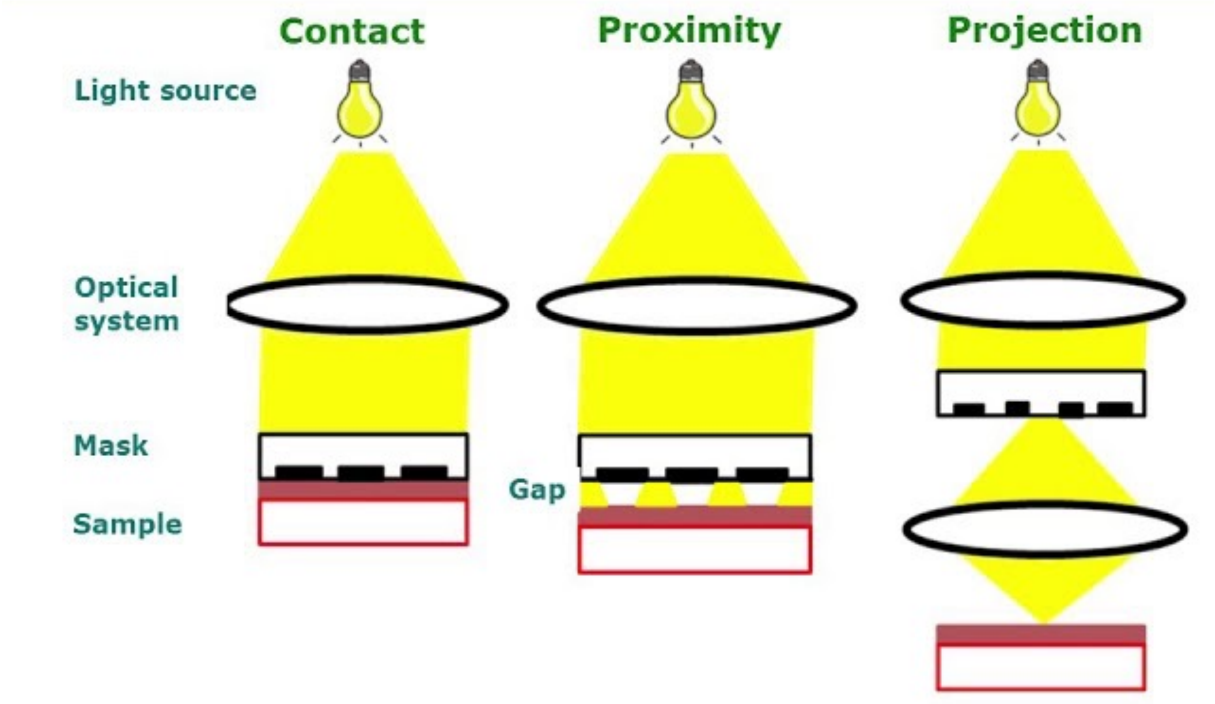
K. Kern courtesy

Top-down techniques



Zheng Cui, Nanofabrication, Principles, Capabilities and Limits, Springer 2024

Photolithography

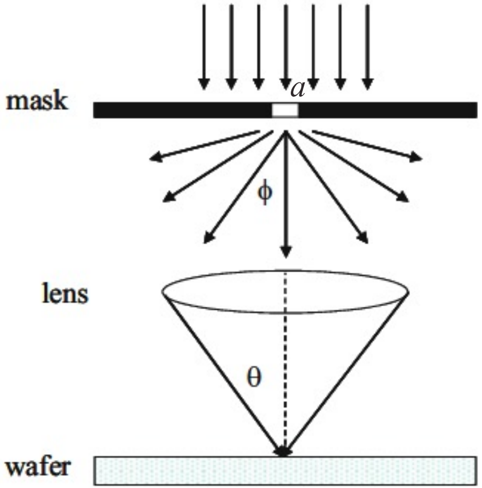


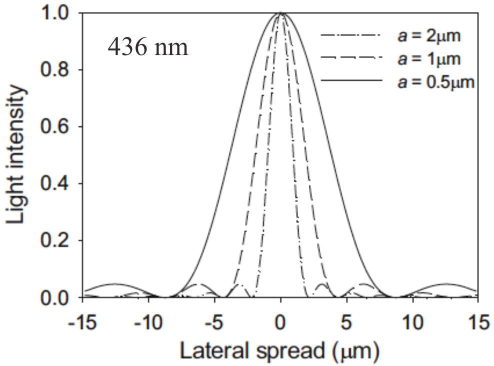
Projection photolithography can project a demagnified image onto the sample (5:1 or 10:1). It is capable of patterning much smaller features as well as eliminating the mask damage and contamination problems associated with contact photolithography

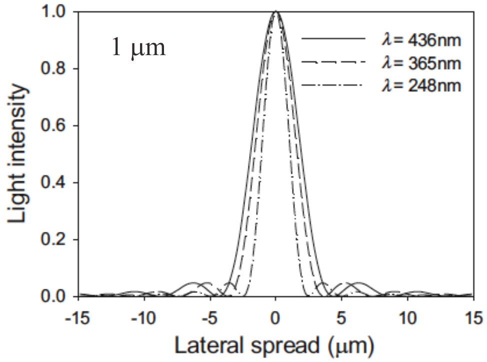
Photolithography – diffraction limit

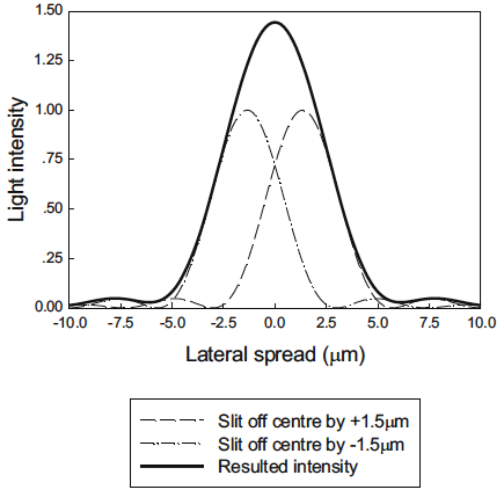
mask opening → slit → diffraction fringes

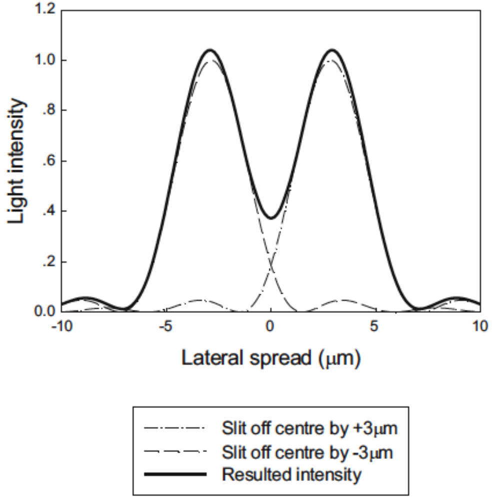
position of the first minimum: $\sin\phi = \frac{\lambda}{a}$











Photolithography – diffraction limit

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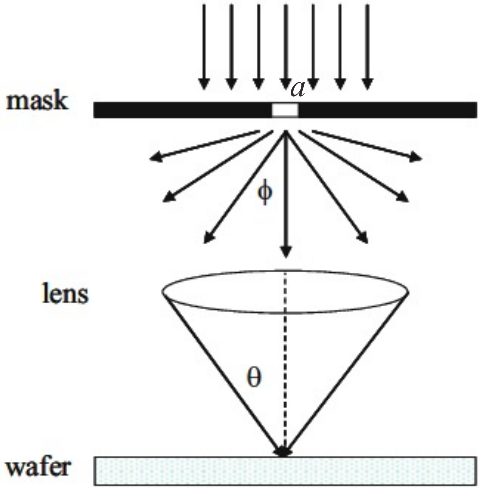
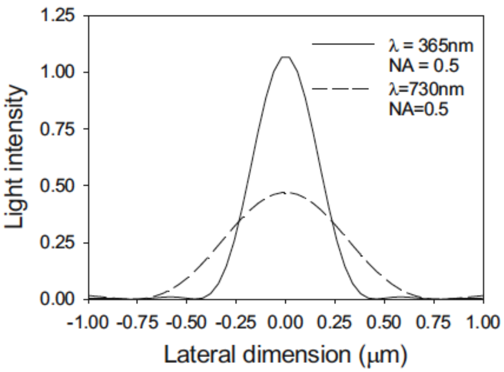
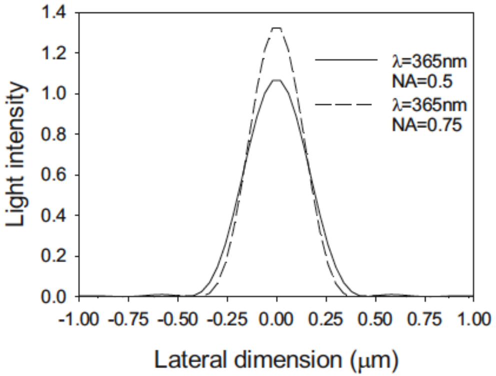


focussing lens: $NA = n \sin\theta$

n refractive index of the medium





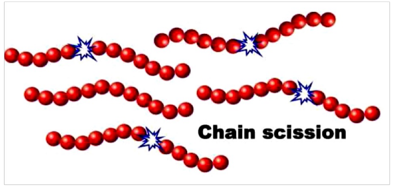
resolution limit of a projection photolithography system (→ size of the smallest feature)

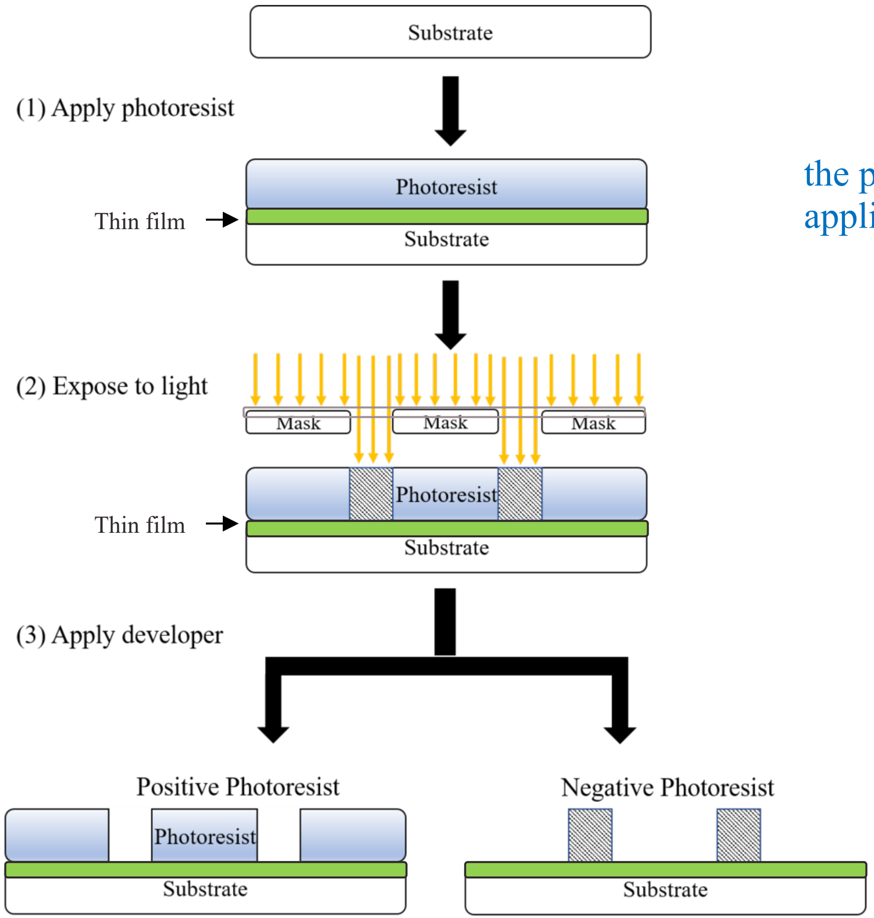
$$R = k_1 \frac{\lambda}{NA}$$

λ is the illumination wavelength, NA is the numerical aperture of the optical system (0.3 - 0.8), and k_1 is a factor related to a specific optical process ($k_1 < 1$, typically $k_1 \approx 0.5$).

Photolithography

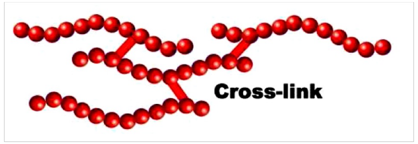
positive resist:
light softens the resist





the photoresist is a polymer applied by spin coating

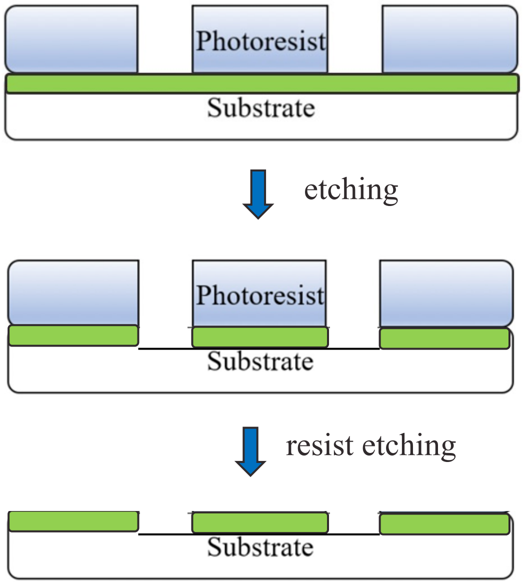
negative resist:
light hardens the resist

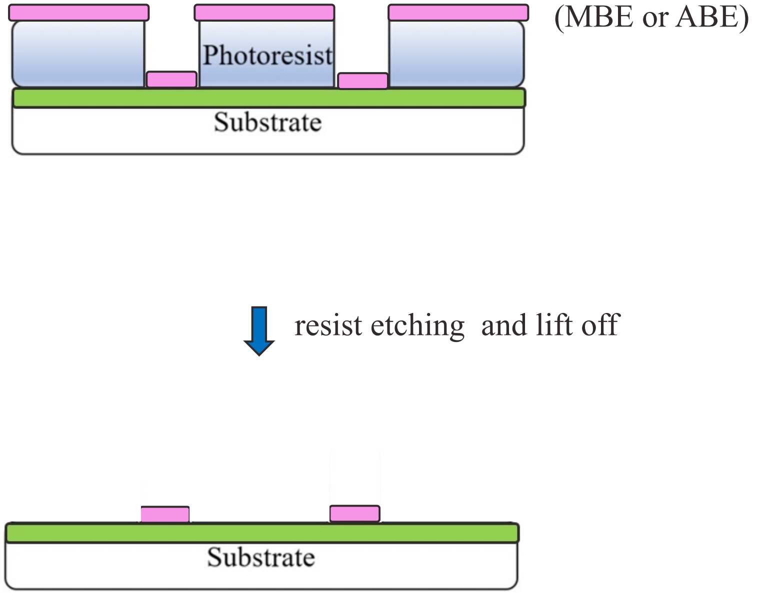


Mask motif transferred to the substrate

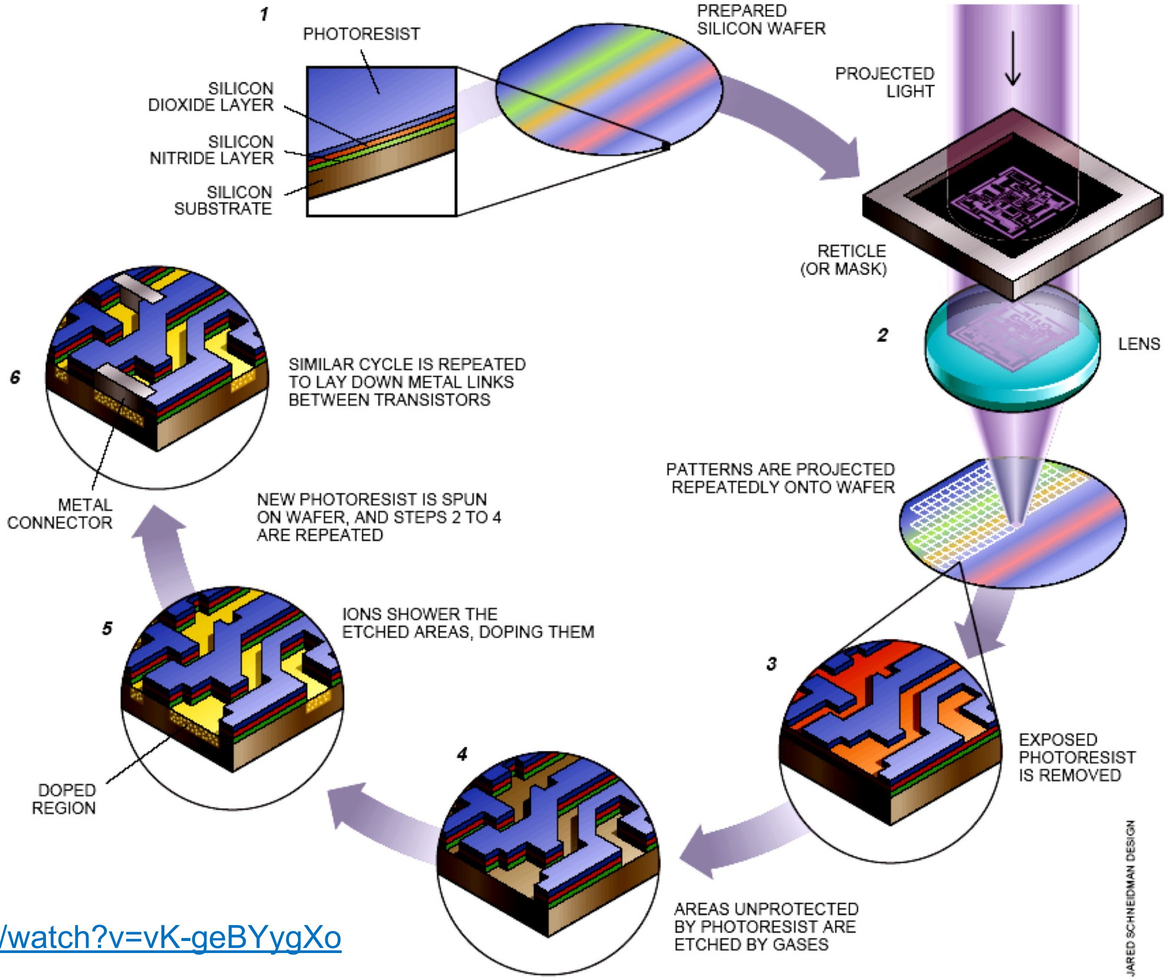
Photolithography

Examples of further steps:



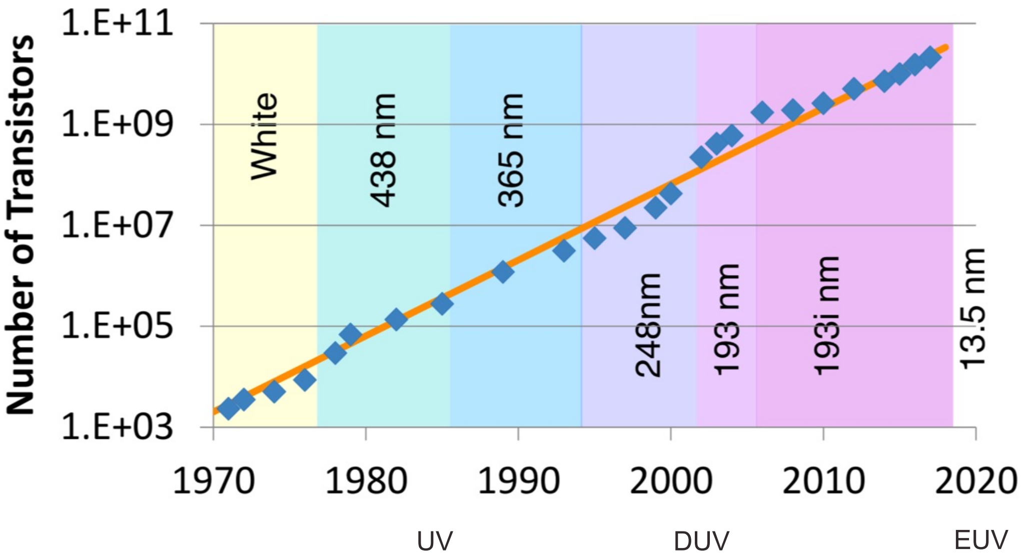


Photolithography



https://www.youtube.com/watch?v=vK-geBYygXo

From visible light to ultraviolet light



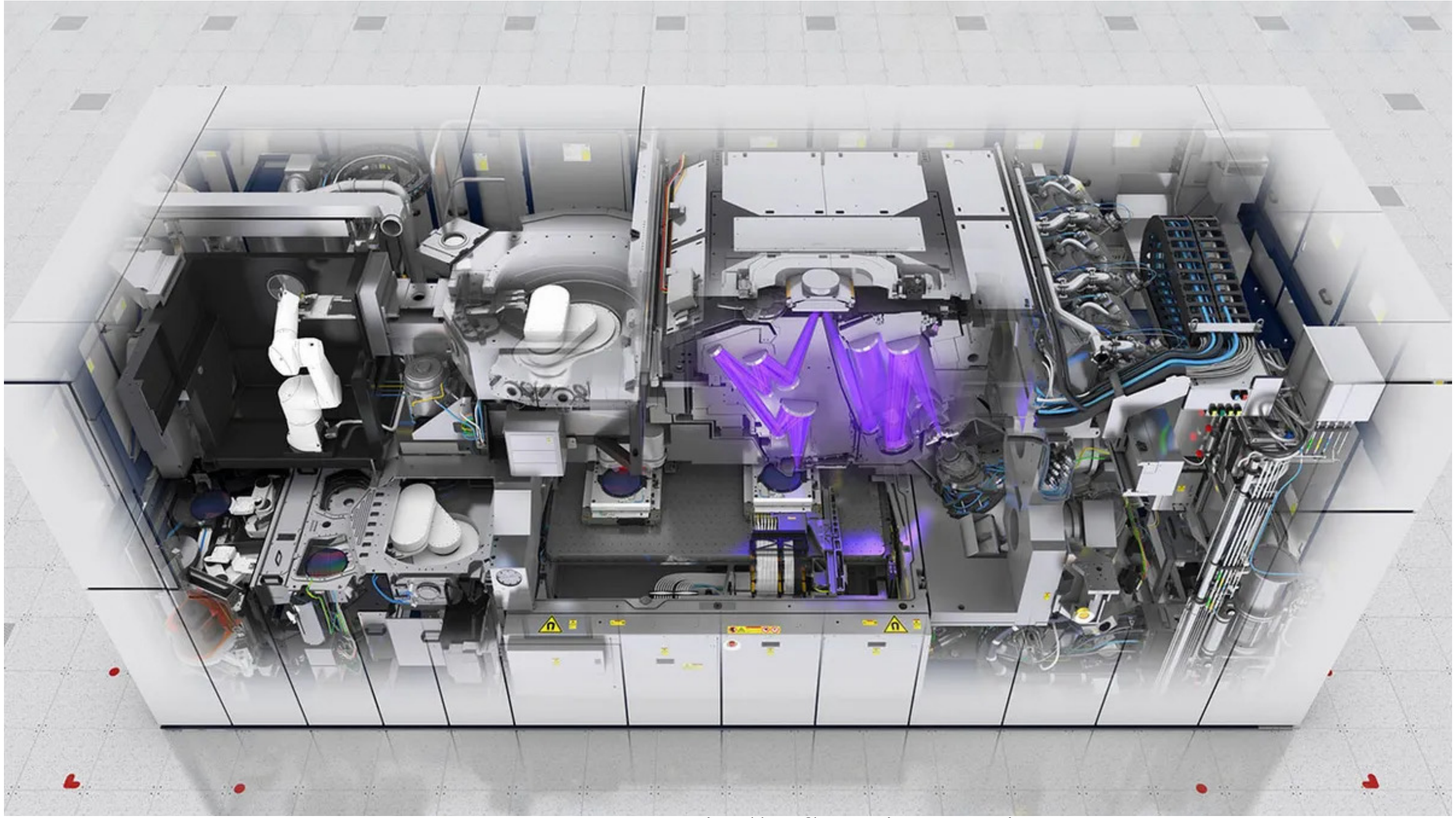
wavelenght limits resolution and therefore the lateral size of the structures

→

from visible to UV, to Deep UV, and to Extreme-UV (13.5 nm)

EUV lithography

https://www.asml.com/en/products/euv-lithography-systems



motorized high-precision positioning of the wafer (sub-nanometer) (ASML)

atomically-flat mirror optics (ZEISS)

vacuum

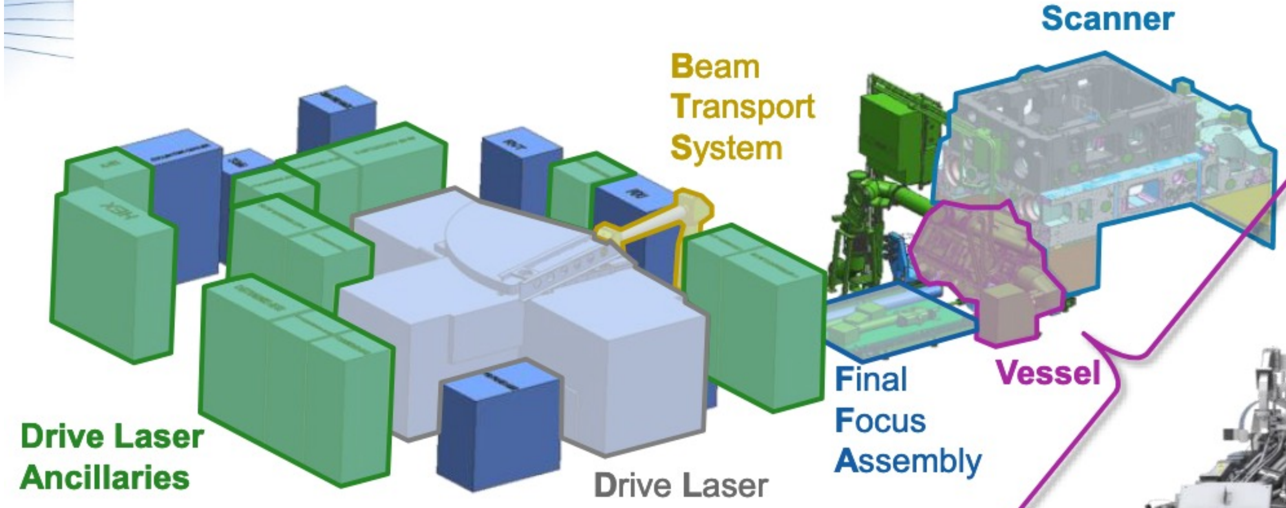
13.5 nm EUV source: Laser-pulsed Sn droplet plasma (TRUMPF)

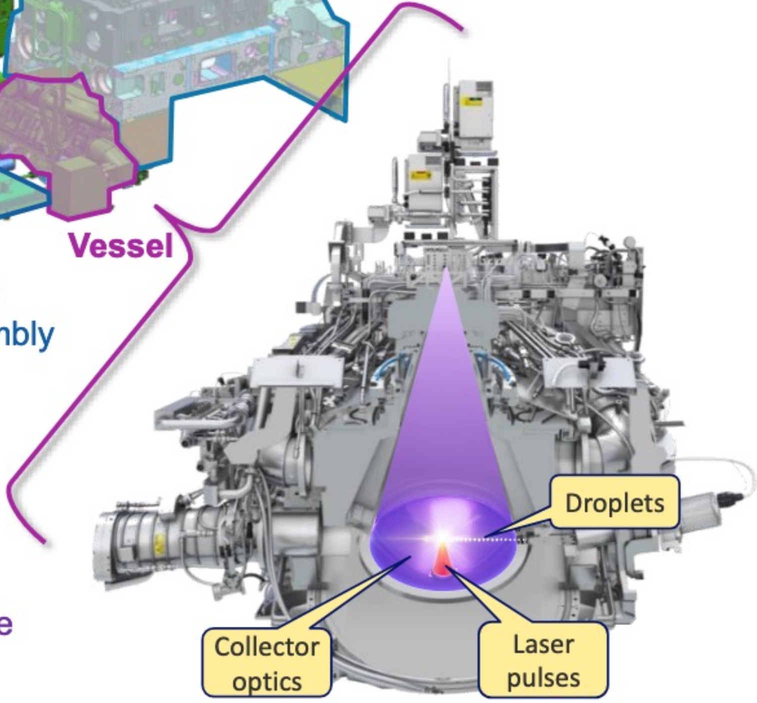
EUV lithography - source

Introduction to the NXE EUV source

ASML

Slide 16





Laser Produced Plasma EUV source

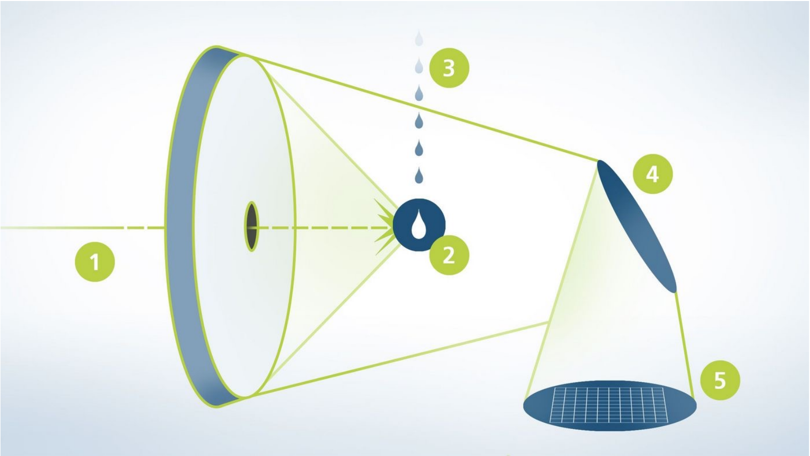
- Droplets (fuel) at 50kHz
- Laser pulses (energy source), Main pulse and Pre pulse
- Collector optics (direct light to scanner)

EUV lithography - source

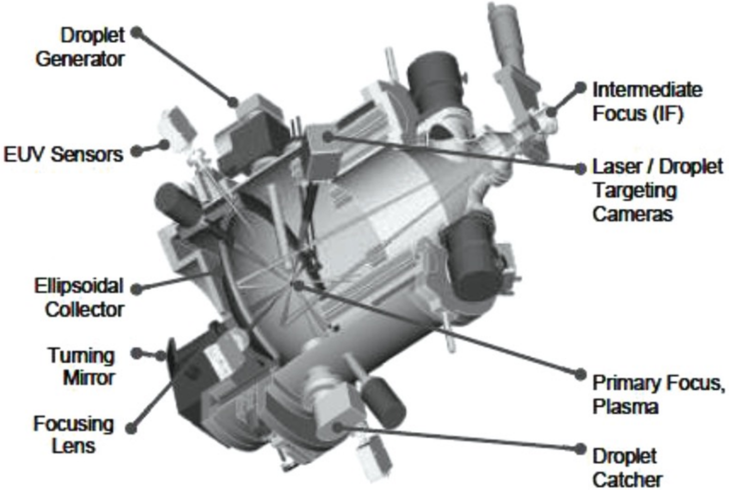
https://www.asml.com/en/technology/lithography-principles/light-and-lasers

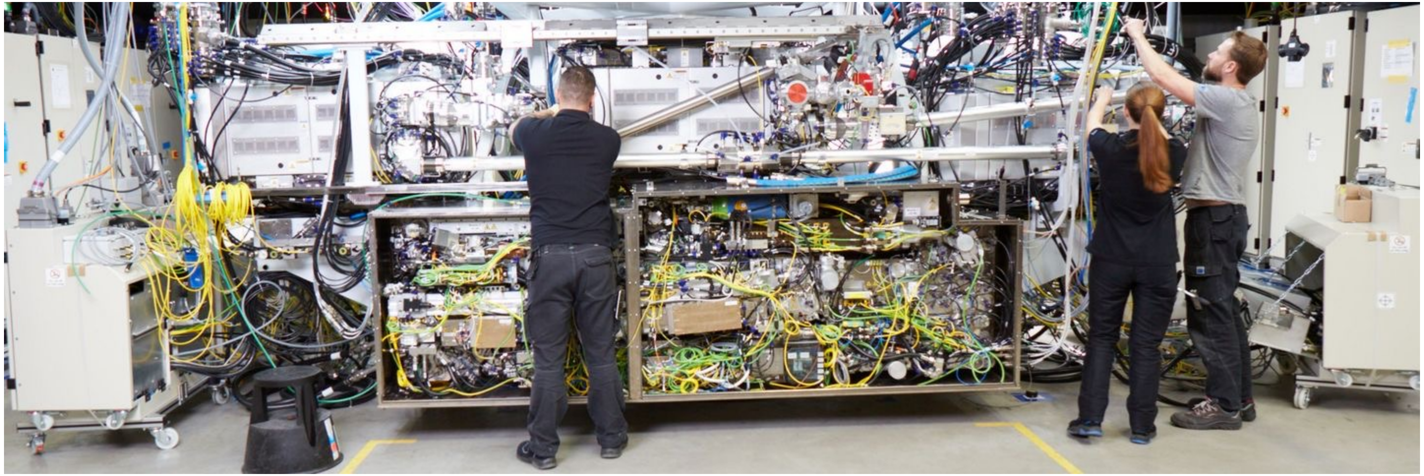
https://www.trumpf.com/en_CA/solutions/applications/euv-lithography/

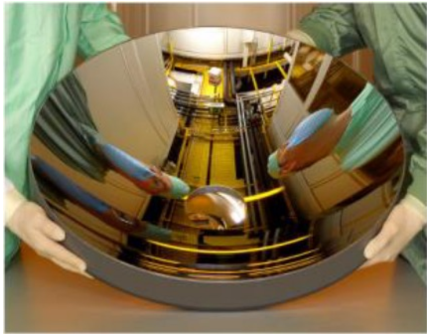
A generator drops tin droplets into a vacuum chamber (3), then a high-power pulsed laser (1) by TRUMPF (CO_2 laser, power amplified 10’000 times) impacts the passing tin (Sn) droplets (2) 50’000 times per second.
The tin atoms are ionized, and an intensive plasma is created. A collector mirror captures the EUV radiation emitted by the plasma in all directions, bundles it, and finally transfers it to the lithography system (4) for exposure of the wafer (5).



Handbook of Laser Micro- and Nano-Engineering, EUV Sources
https://link.springer.com/referenceworkentry/10.1007/978-3-030-63647-0_54

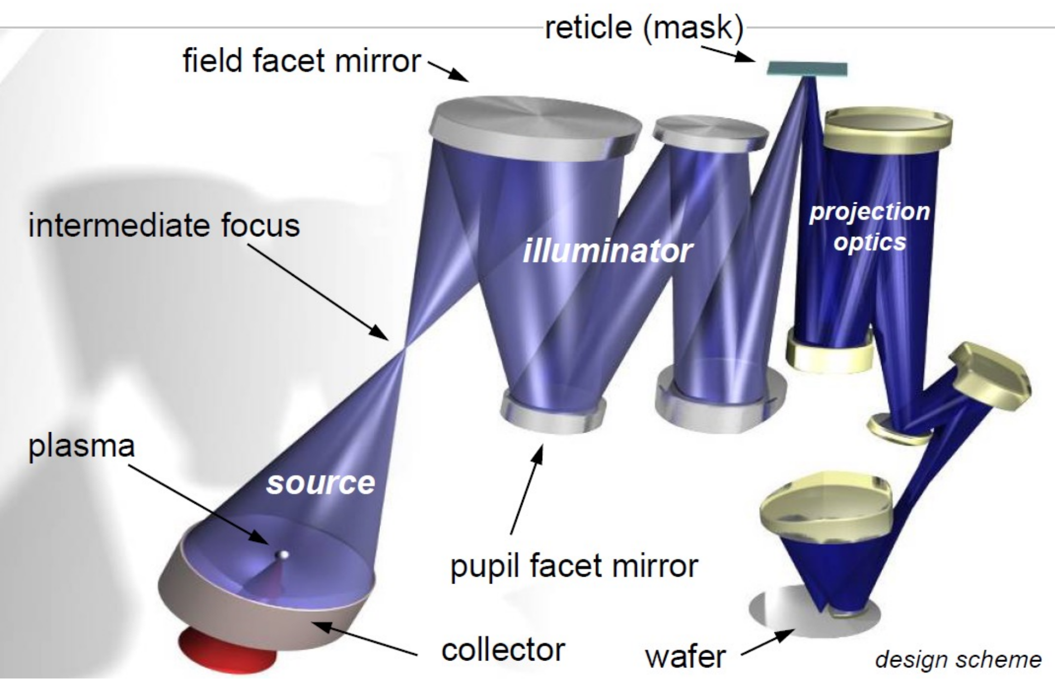

Droplet Generator
EUV Sensors
Ellipsoidal Collector
Turning Mirror
Focusing Lens
Intermediate Focus (IF)
Laser / Droplet Targeting Cameras
Primary Focus, Plasma
Droplet Catcher





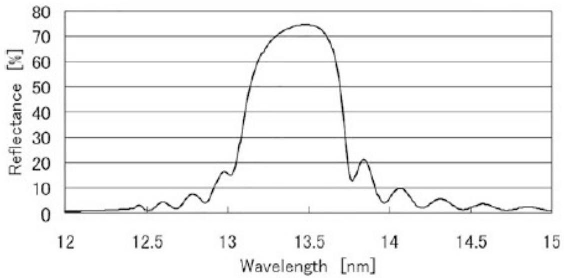
EUV lithography - optics

EUV optical train (schematic).



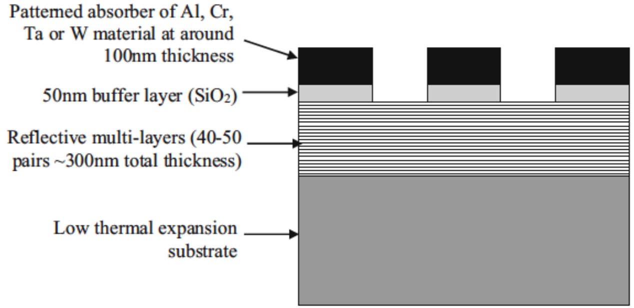
Limit ~10 nm

mirrors in place of lenses



Theoretical reflectivity of a mirror consisting of Mo-Si multilayer at normal incidence of EUV radiation

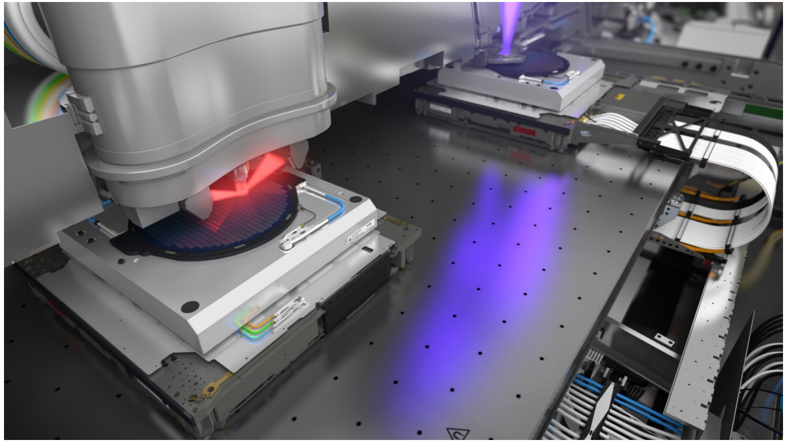
mask in reflection

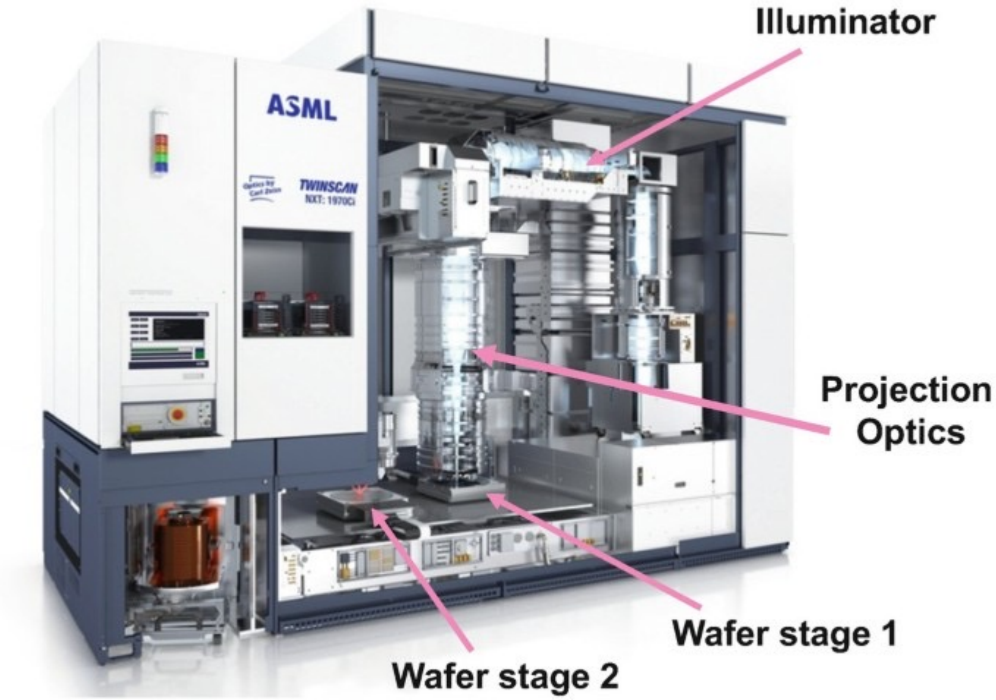


https://www.euvlitho.com/2018/P22.pdf

EUV lithography - positioning

https://www.asml.com/en/technology/lithography-principles/mechanics-and-mechatronics

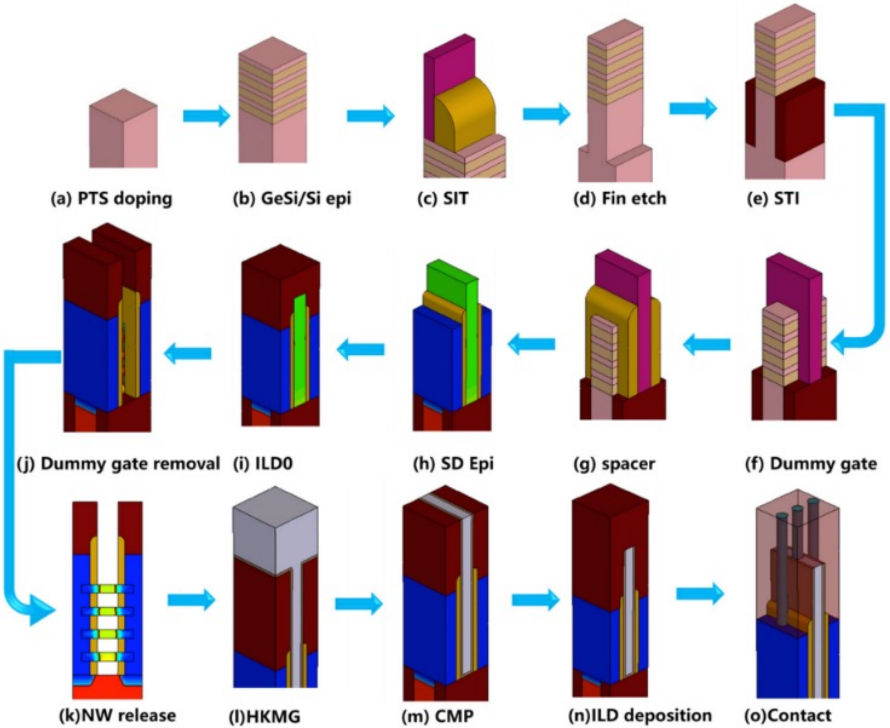


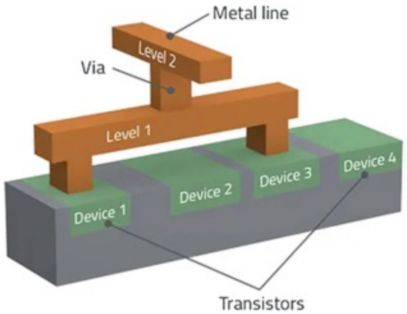


measure positioning 20’000 times per second with an accuracy of 60 pm

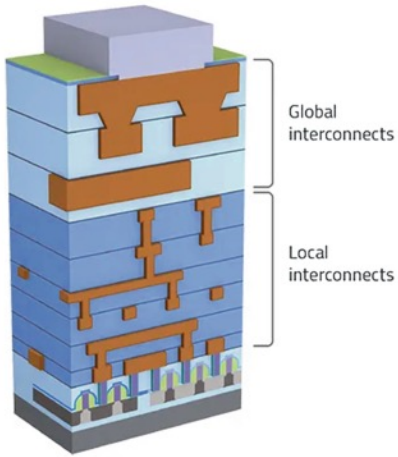
loading the wafer into the system, printing the pattern in almost 100 different places and then unloading the wafer as many as 275 times an hour;
magnetically levitating wafer tables

Chip fabrication – Process flow





(a)

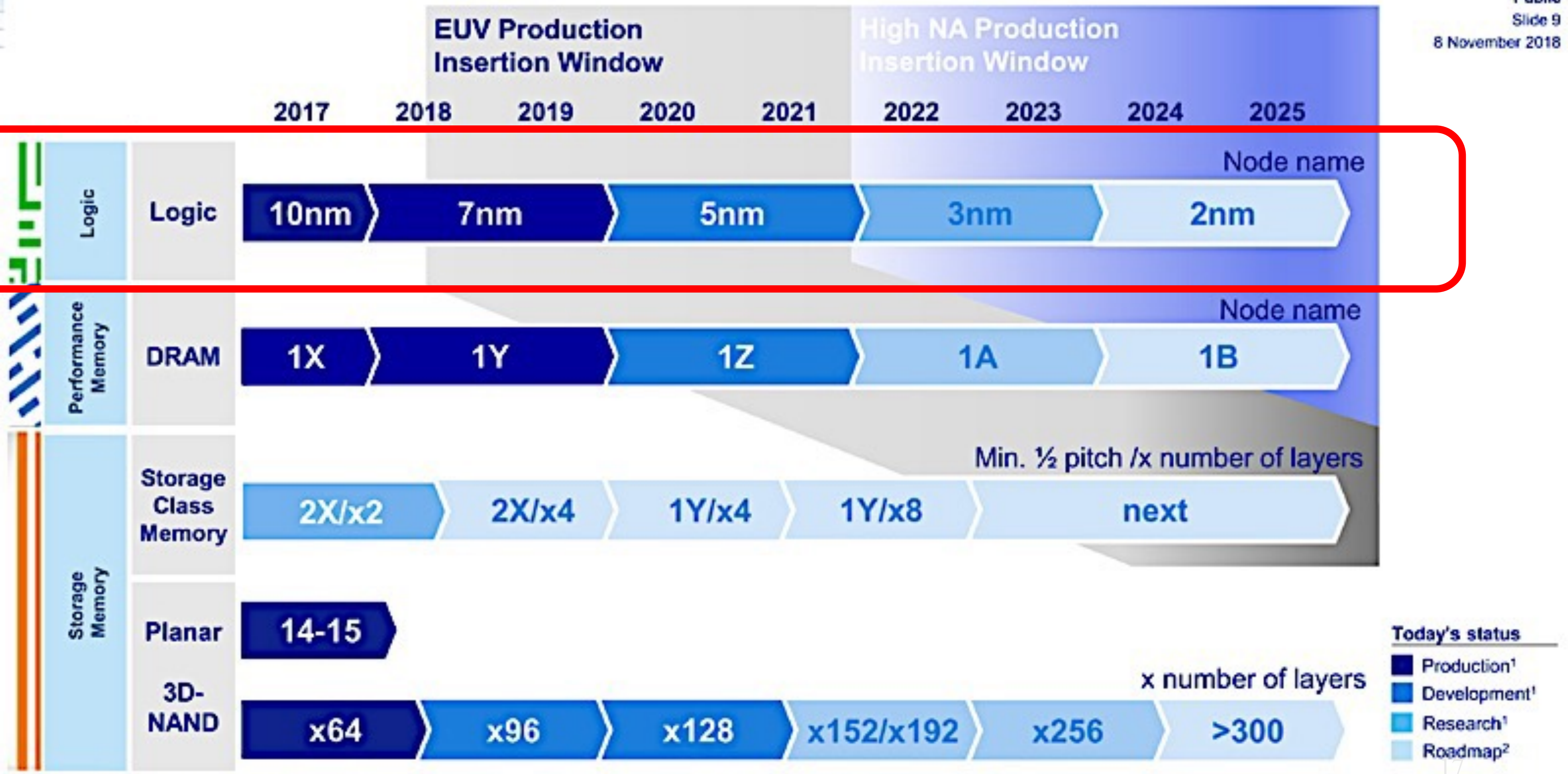


(b)

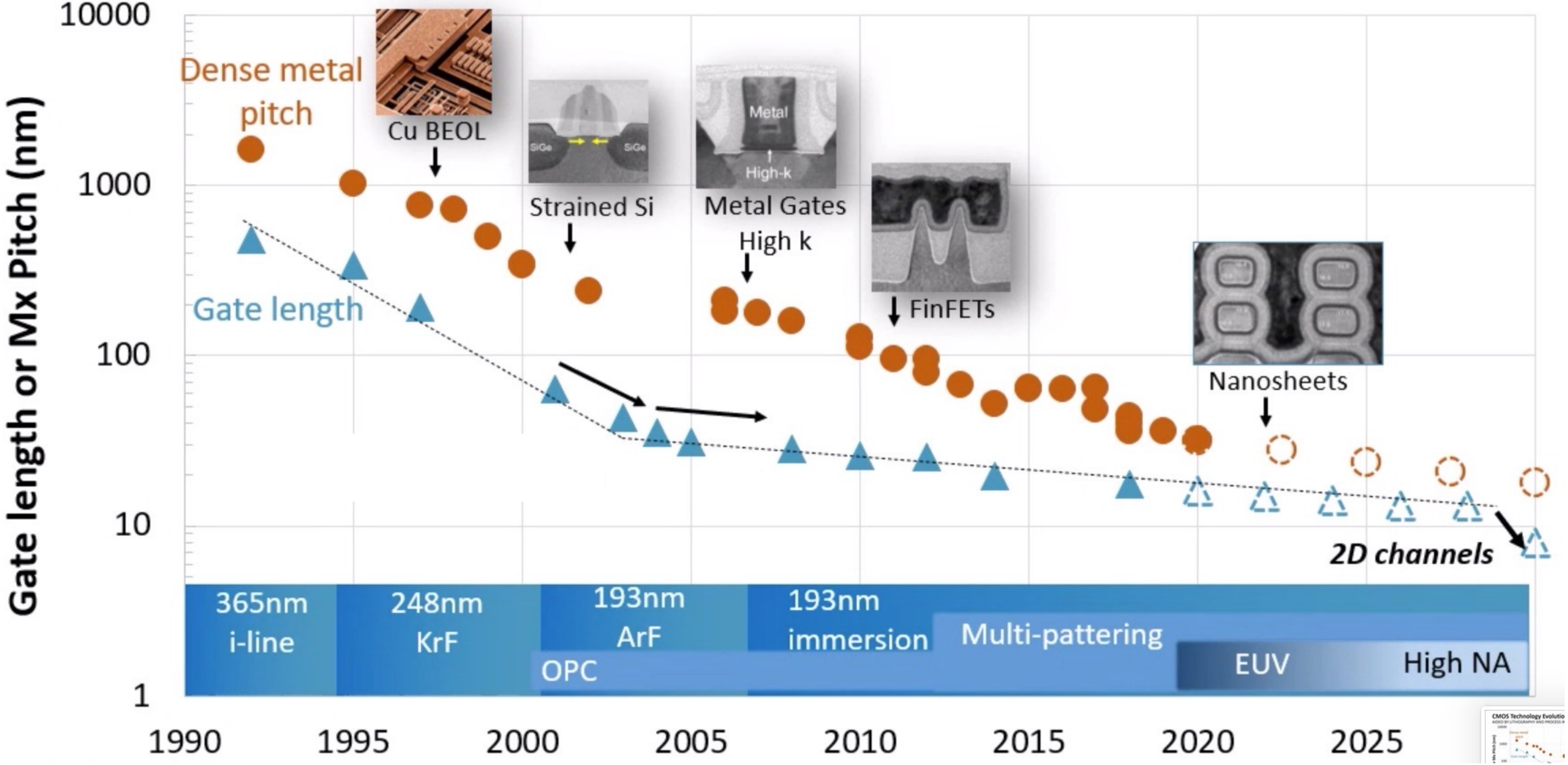
Customers' scaling roadmaps continue

ASML

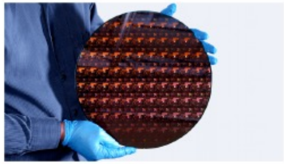
Public
Slide 9
8 November 2018



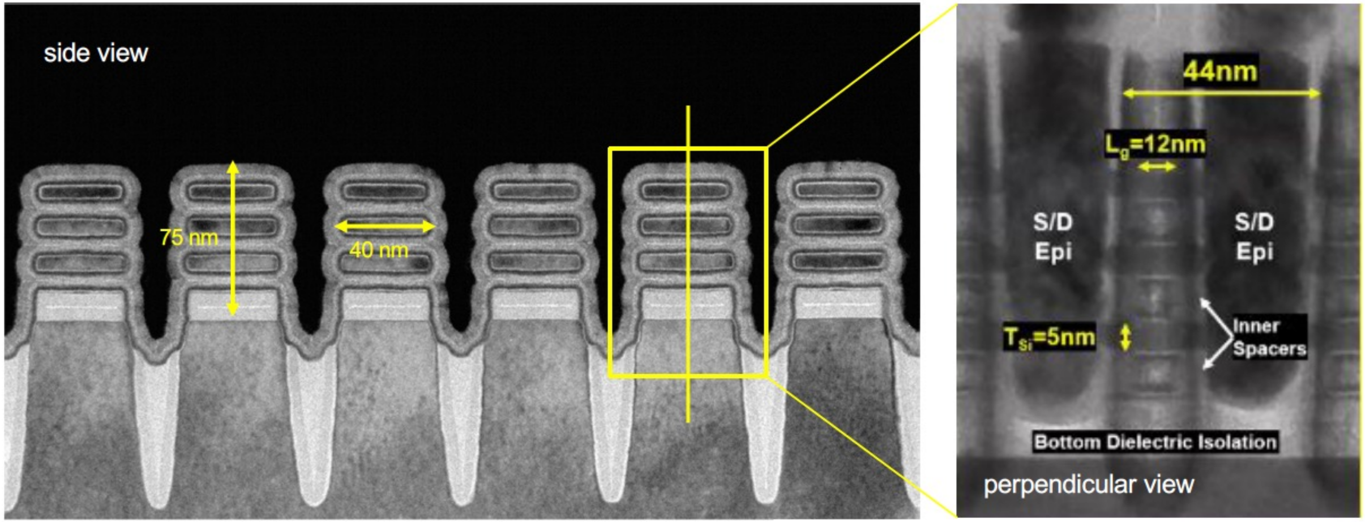
Source: [1] Customers public statements, IC Knowledge LLC; [2] ASML extrapolations



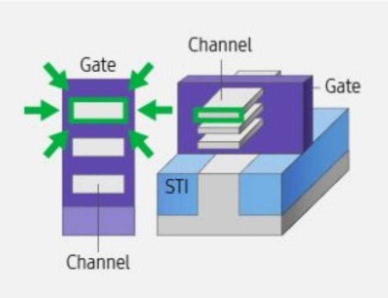
Gate length or Mx Pitch (nm)
10000
1000
100
10
1
Dense metal pitch
Cu BEOL
Strained Si
SiGe
Metal Gates High k
Metal
High-k
FinFETs
Nanosheets
Gate length
2D channels
365nm i-line
248nm KrF
193nm ArF
193nm immersion
Multi-pattering
OPC
EUV
High NA
1990
1995
2000
2005
2010
2015
2020
2025

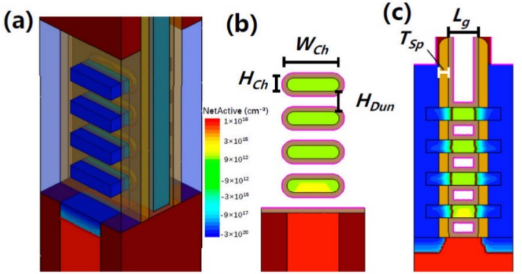


IBM – 2 nm Nanosheet Transistor



12 nm gate length!





GAA-FETS
nanosheet

e-beam lithography

Based on scanning electron microscope (SEM) technology

Electrons in place of photons $\lambda = \dfrac{h}{\sqrt{2\,m\,E}} \rightarrow \lambda = \dfrac{1.23}{\sqrt{eV}}$ nm (non-relativistic approximation)

100 eV $\rightarrow$ $\lambda = 0.12$ nm electron wavelength is not the resolution-limiting factor in e-beam lithography

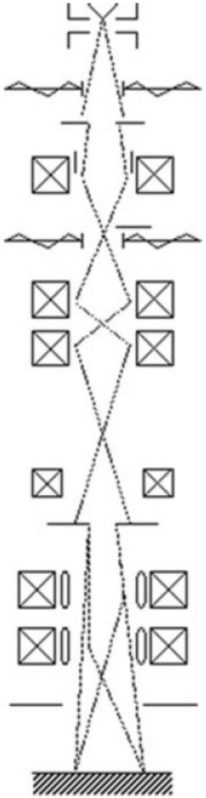
the resolution is limited by electron optic aberration and electron scattering in the resist

scanning a focused beam of electrons
→
“draw” patterns on a surface covered with an electron-sensitive film (resist)

high resolution
flexible (research, prototypes)

low throughput (serial exposure)

e-beam lithography



(a) (b)

Fig. 3.7 (**a**) Photograph of an e-beam lithography system (VB6-HR from Leica Microsystems) and (**b**) schematic of complete electron optical system in an e-beam lithography column

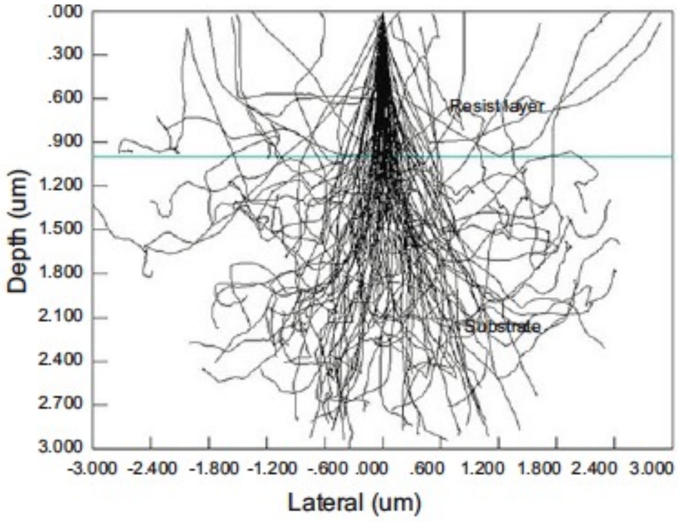
10 – 200 keV

high energy allows to reduce chromatic and space charge aberrations

→ smallest possible spot size

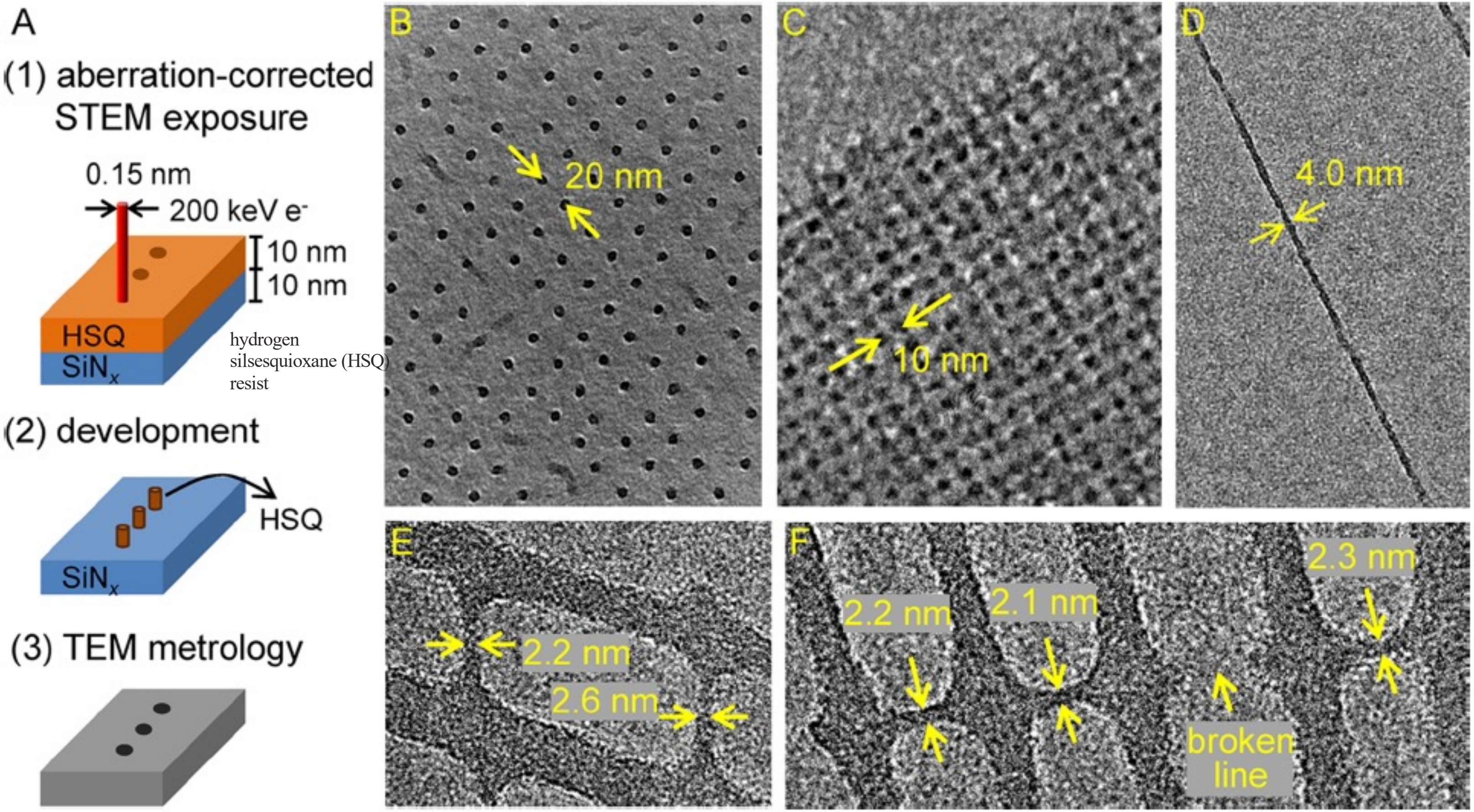
e-beam lithography - Scattering and proximity effect

To realize nanoscale lithography with electron beam, a small beam size is necessary but not enough.
Electrons have to interact with a polymer resist, so that the energy carried by the electrons is transferred to the polymer material, causing modifications to the molecular chains. The energy transfer process takes place in the collisions (scattering) between the electrons and the atoms in the polymer. The energy transfer is responsible for the polymer modification. The process can lead to a much larger area of energy deposition than the original size of beam landing area, creating the so-called proximity effect.



Monte Carlo simulations: trajectories of 100 electrons showing the spatial extent of electron scattering
(20 keV beam energy, 1 μm resist thickness, Si substrate)

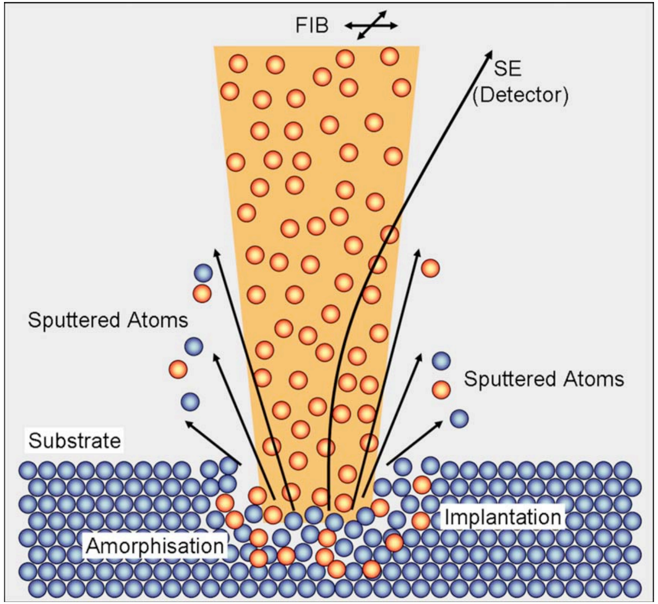
e-beam lithography: resolution limit



STEM = Scanning Transmission Electron Microscope

V.R. Manfrinato et al., Nano Lett. **13**, 1555 (2013)
https://pubs.acs.org/doi/10.1021/nl304715p

Focused ion beam (FIB)



Ions impinging at 1 – 50 keV

Ions in place of electrons, much larger mass
→
Ion bombardment directly erodes the substrate to design the desired pattern

Spatial resolution of about 5 nm

It is a serial process (like e-beam lithography) → quite slow (typically used to shape the masks for photolithography)

Ion sources:
- liquid metal ion source
- gas field ion source (He, Ne, Xe)

DOI: 10.1116/1.2955728

Nanoimprint lithography

Seal printing into wax

Nanoimprint lithography

replication from a (soft) stamp

simple and cheap

parallel process / roll

no diffraction-induced limit on imaging resolution

can achieve sub-10 nm resolution patterning

many developments and variants

but:

distortions or deformations (pressing), leading to misalignments

still young technique

about stamps:

commonly used materials for stamps:
silicon, silicon dioxide, silicon nitride, or metals

for sub-100 nm features:
stamps made by e-beam lithography patterning of resist and then transferred into substrate materials

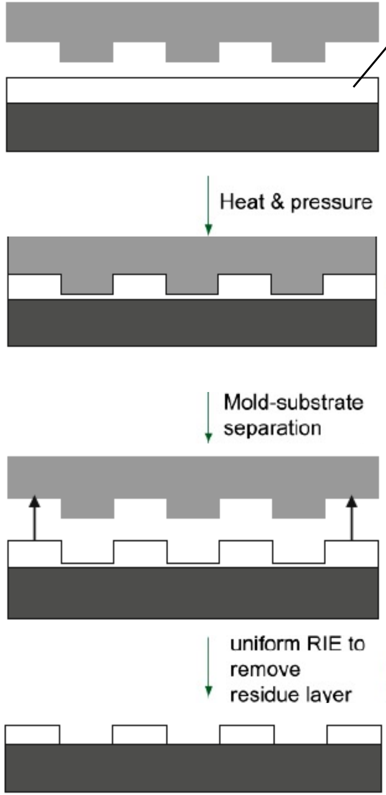
best and most durable stamps:
made of nickel

Zheng Cui, Nanofabrication, Principles, Capabilities and Limits, Springer 2024

Photonics insights **2,** R04 (2023) https://doi.org/10.3788/PI.2023.R04

Thermal nanoimprint lithography (T-NIL)

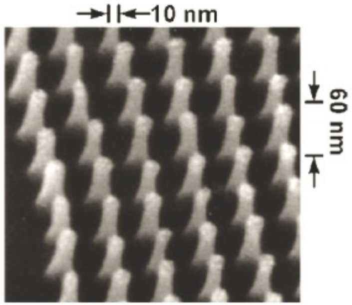
thermoplastic resist, *e.g.*, PMMA (glass transition temperature $T_g \approx 100^\circ C$)



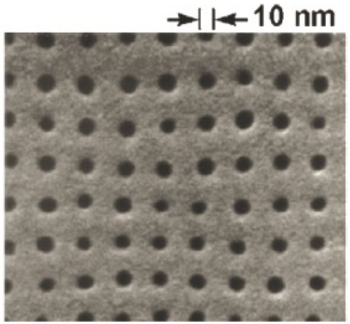
$T > T_g$

$T < T_g$

reactive ion etching for pattern transfer into substrate



mold



hole array in PMMA

Stephen Y. Chou et al., *J. Vac. Sci. Technol. B* **15**, 2897–2904 (1997) https://doi.org/10.1116/1.589752

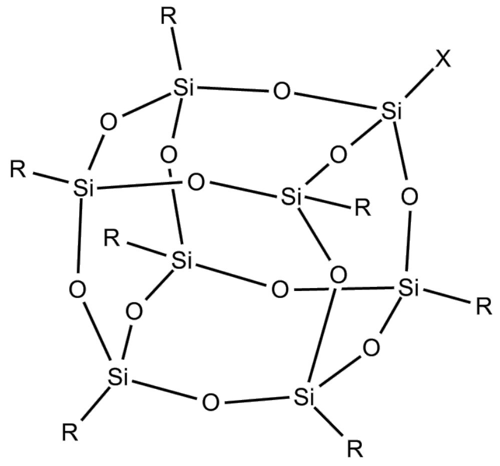
Room temperature nanoimprint lithography (RT-NIL)

same principle but uses polymers with low glass-transition temperature

T_g = 0-10°C, T melting = 30°C

example: Hydrogen silsesquioxane (HSQ), negative resist

no need for thermal treatment



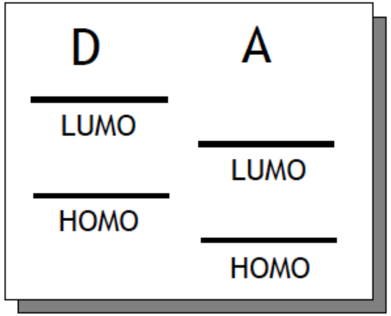
UV-cured nanoimprint lithography (UV-NIL)

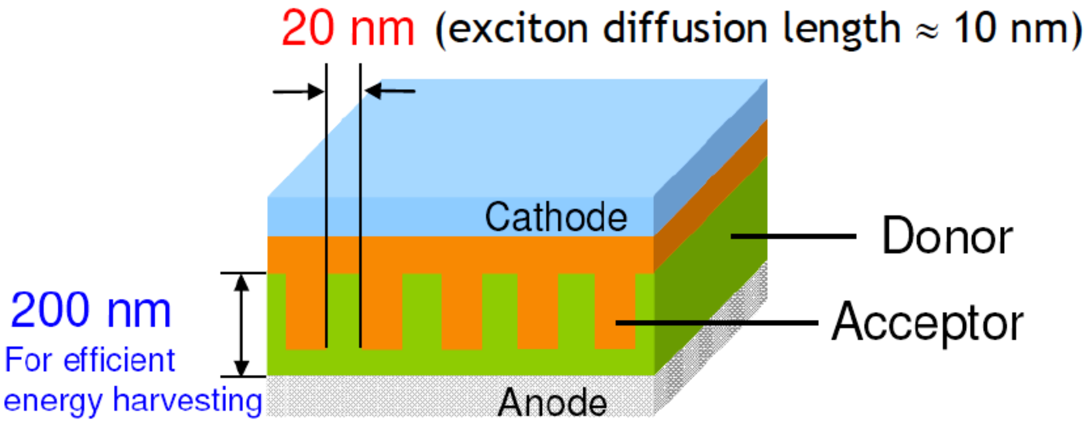
resist is cured by exposure to UV light

no need for thermal treatment

Application: Organic solar cells

ideal structure:



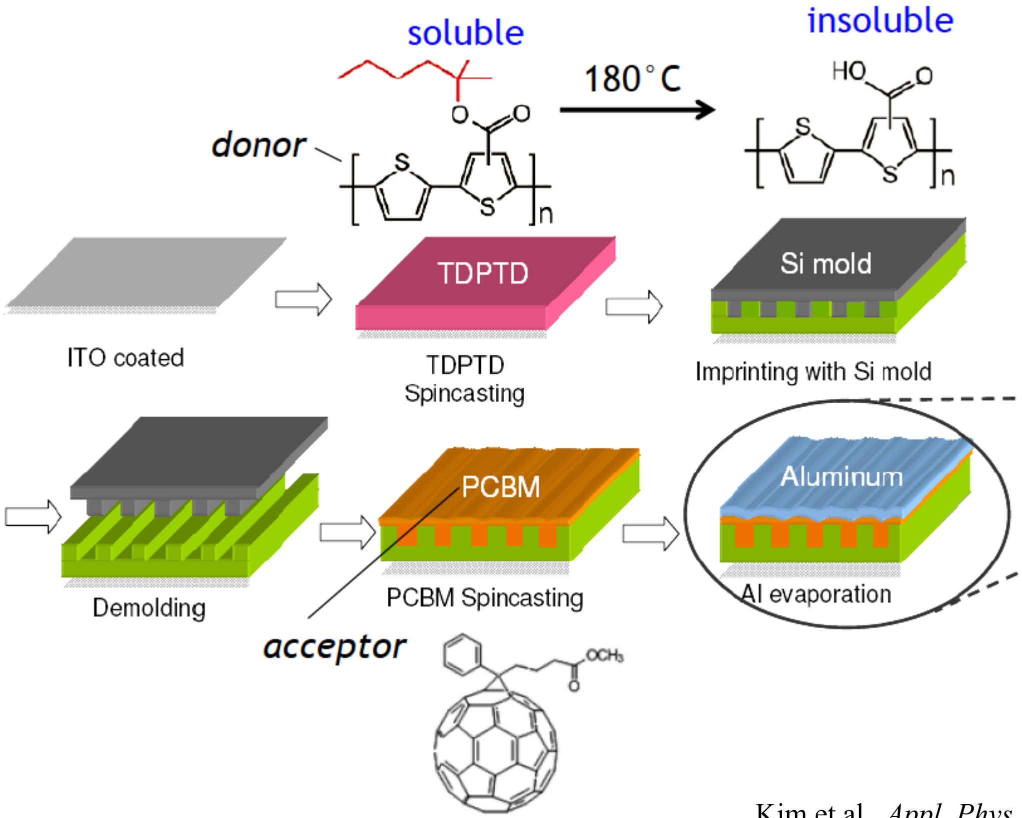


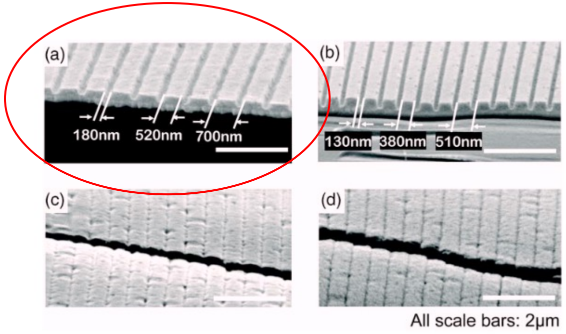
improve charge transport while maintaining a high interfacial area

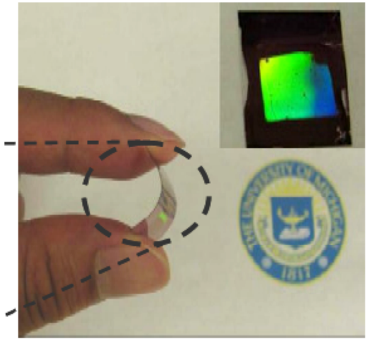
Kim et al., *Appl. Phys. Lett.* 90, 123113 (2007)
https://doi.org/10.1063/1.2715036

Nanoimprint lithography

Organic solar cell fabrication

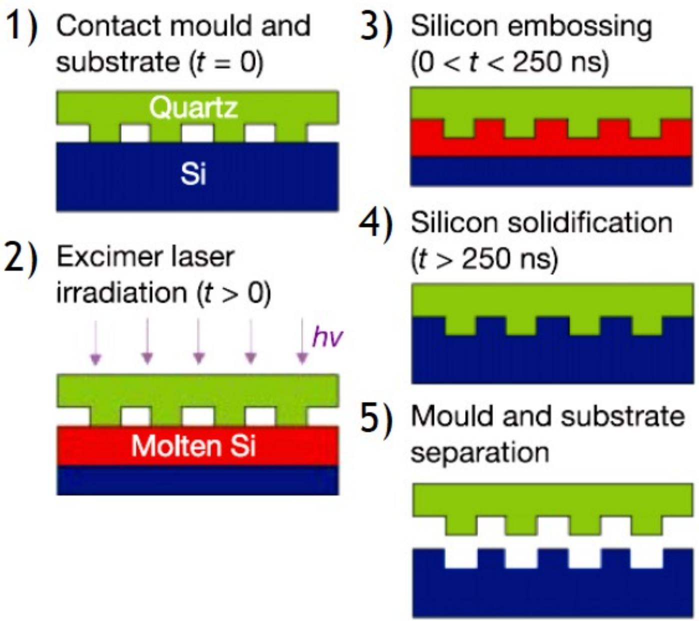


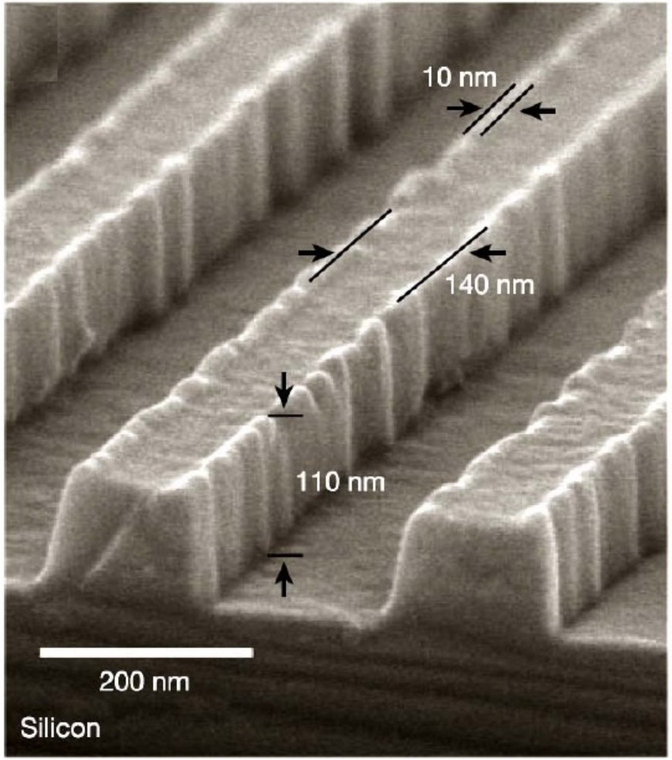




Kim et al., *Appl. Phys. Lett.* 90, 123113 (2007)
https://doi.org/10.1063/1.2715036

Direct Si nanoimpriting

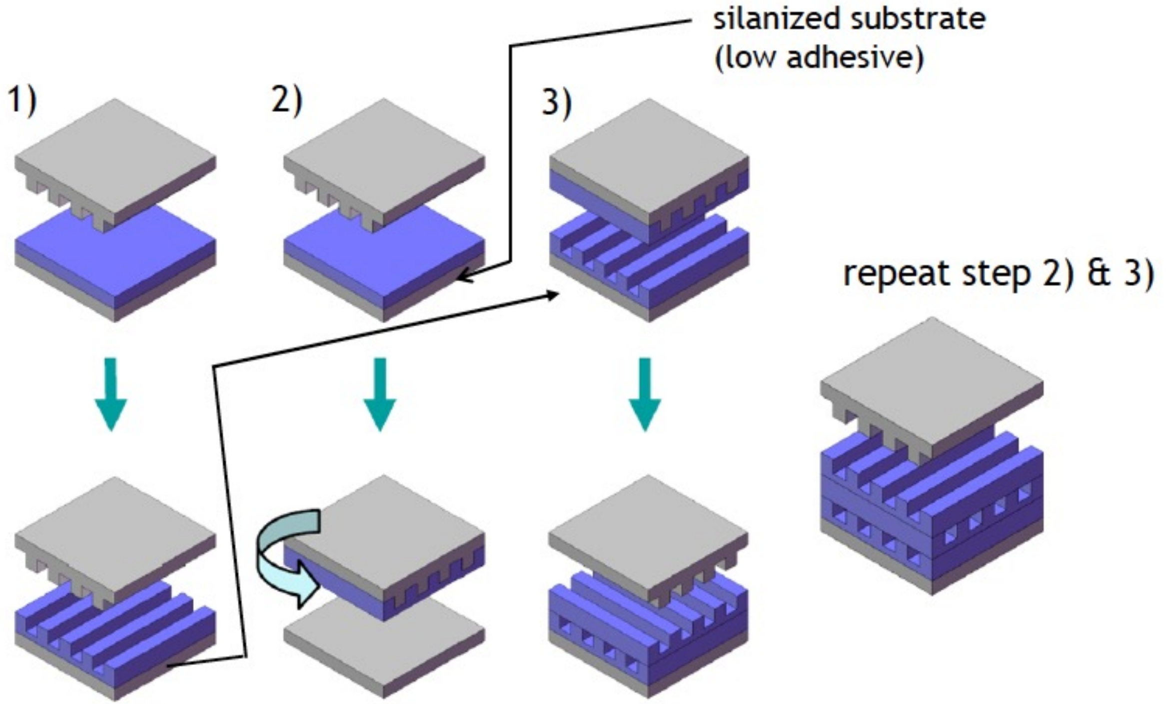


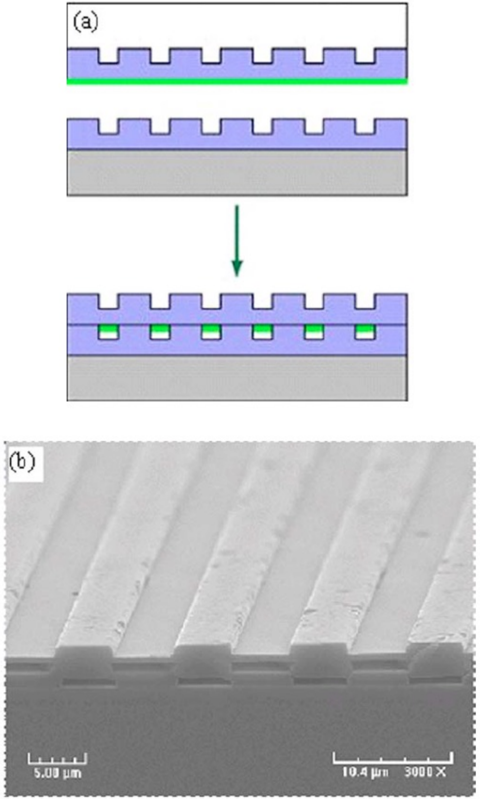


S.Y. Chou et al.; Nature 417 (2002), 834.

Nanoimprint lithography

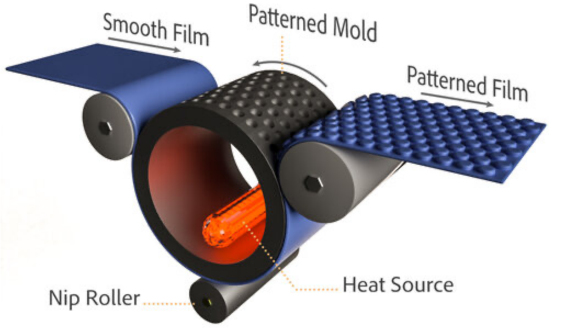
Toward 3D patterning

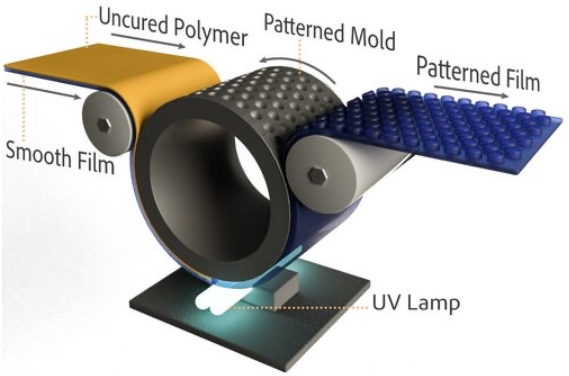


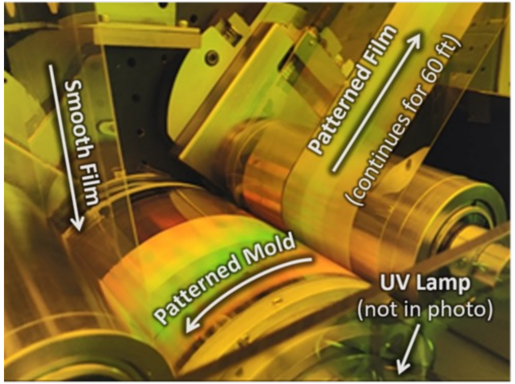


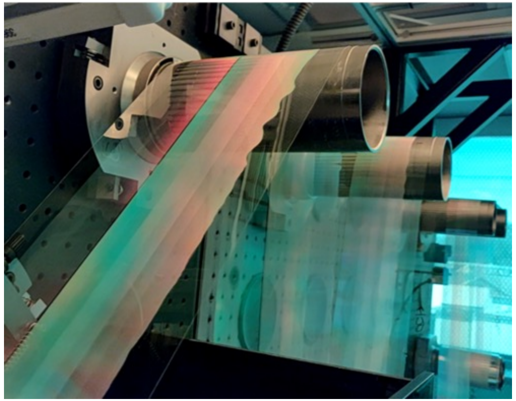
H. Park et al.; J. Vac. Sci. Technol. B 25 (2007), 2325.

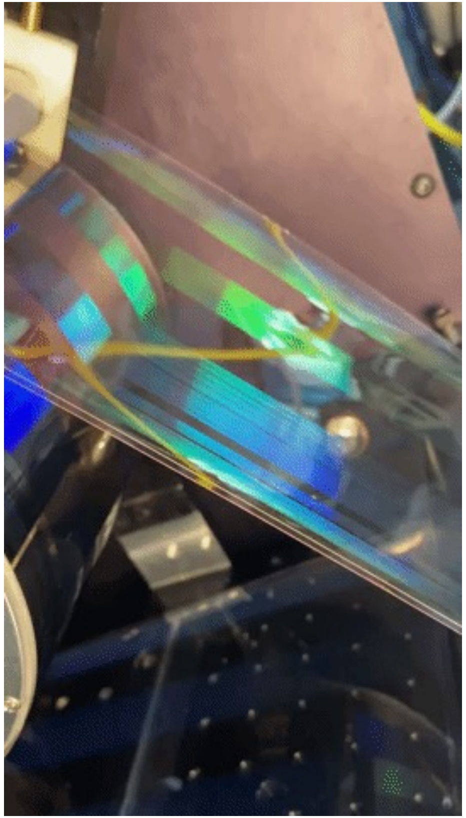
Roll-to-roll Nanoimprint lithography (R2R-NIL)











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resolution: 100 nm features have been reported in laboratory,
such patterning dimension has not been realized at industrial scale