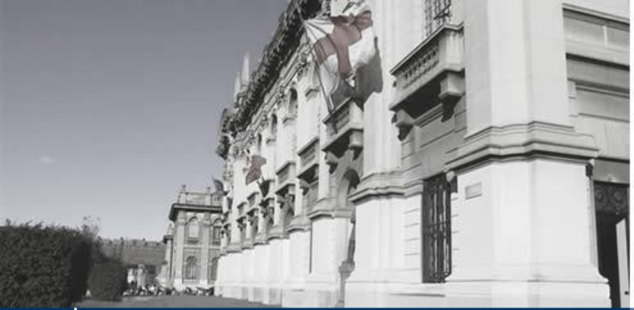

POLITECNICO DI MILANO

    

Nanofabrication of 2D Devices

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Politecnico di Milano, Polo Regionale di Como, Italy

lness.como.polimi.it/ndg.php

Overview

Lithography used in micro/nanoelectronic fabrication

Resist exposure

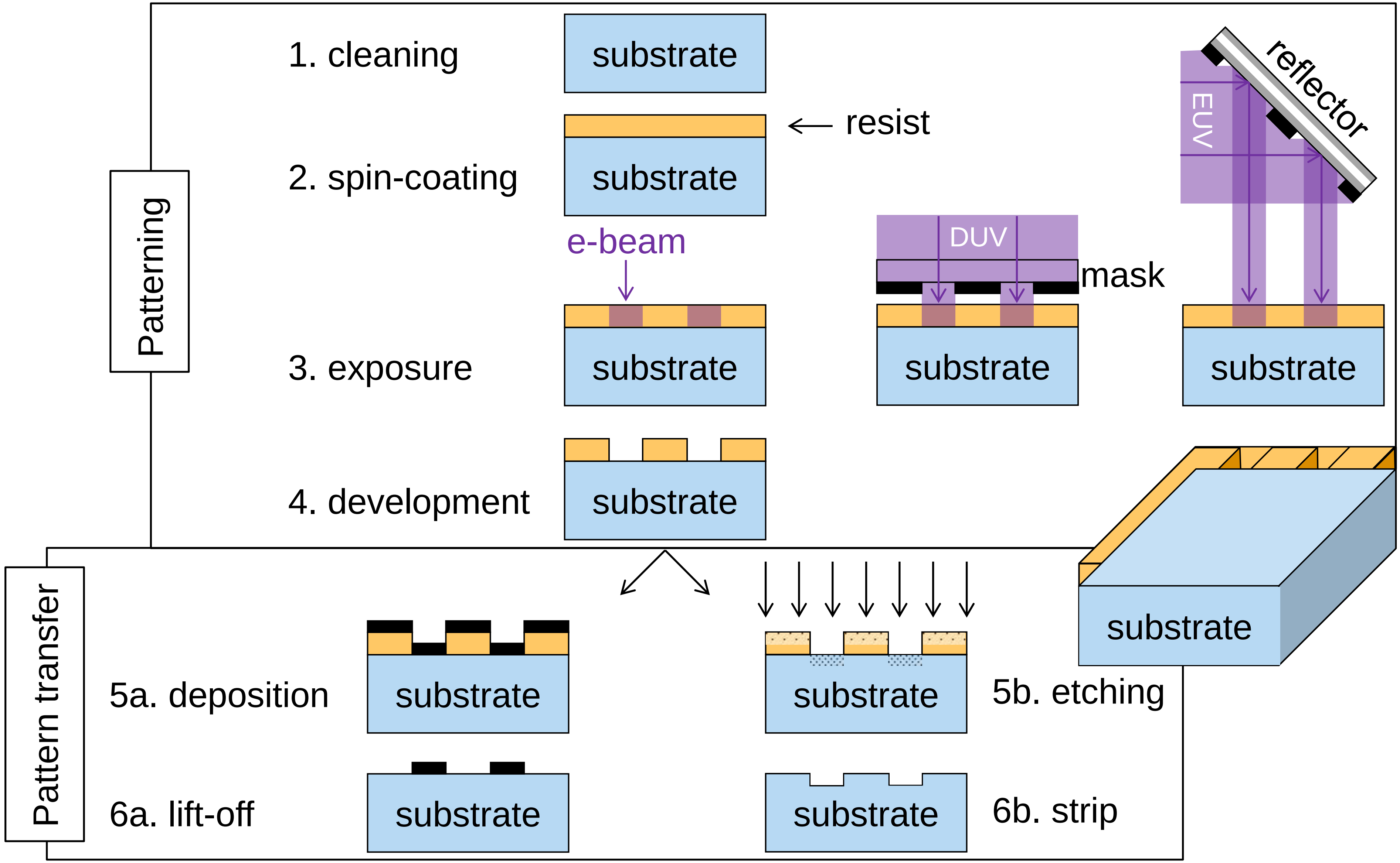
- Optical lithography (UVL, DUVL and EUVL)
- Electron beam lithography (EBL)

Mechanical deformation of resist

- Nanoimprint lithography (NIL)

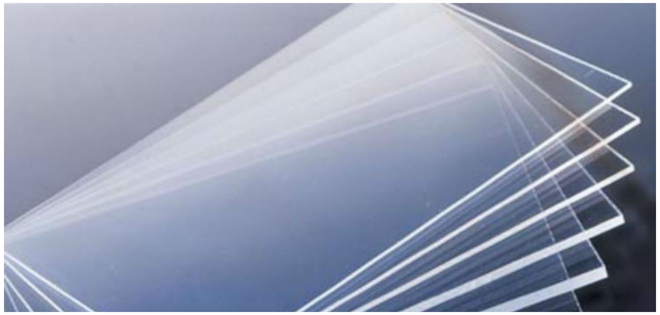
Resistless

- Focused ion beam (FIB) lithography
- Atomic force microscopy (AFM) lithography



Patterning
1. cleaning
substrate
2. spin-coating
substrate
resist
3. exposure
e-beam
substrate
DUV
mask
substrate
EUV
reflector
substrate
4. development
substrate
substrate
Pattern transfer
5a. deposition
substrate
substrate
5b. etching
6a. lift-off
substrate
substrate
6b. strip

Polymethyl-methacrylate (PMMA)



- Very high resolution
- Positive tone
- No shelf life or film life issues
- Not sensitive to white light
- No surface preparation is necessary
- Excellent adhesion to most surfaces
- Diluted in chlorobenzene (C_6H_5Cl) or anisole
- Price > 1 EUR / ml

950K = Molecular weight
1.5 % = Dilution ratio
1.5 % PMMA
98.5 % CB

PMMA, 950K, 2.5 %, 130 nm

Substrate (Si/SiO_2)

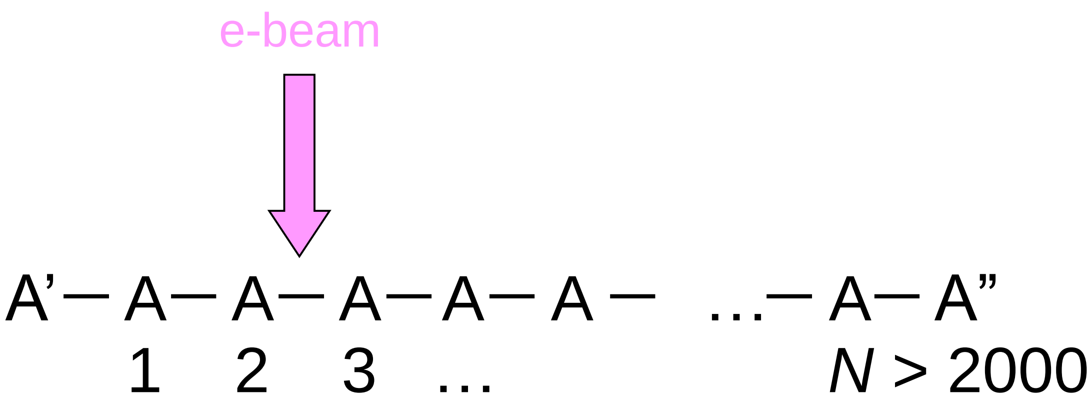
Etching

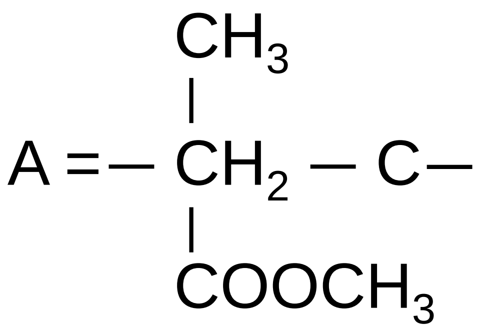
PMMA, 950K, 1.5 %, 50 nm

PMMA, 200K, 3.5 %, 150 nm

Substrate (Si/SiO_2)

Lift-Off





Positive resists (PMMA):
- Average molecular weight is reduced
- Exposed area becomes more soluble

Negative resist (HSQ):
- Average molecular weight is increased
- Exposed area becomes less soluble
  (HSQ = Hydrogen SilsesQuioxane)

Scanning Electron Microscope

Gun power supply

Cathode assembly + first condenser lens

Upper chamber (p ~ 10^{-9} mbar)

Acceleration anode

Gun alignment coils (tilt and shift)

Second condenser lens

Lower chamber (p ~ 5 x 10^{-8} mbar)

Upper column isolation valve

Final aperture + beam blanker

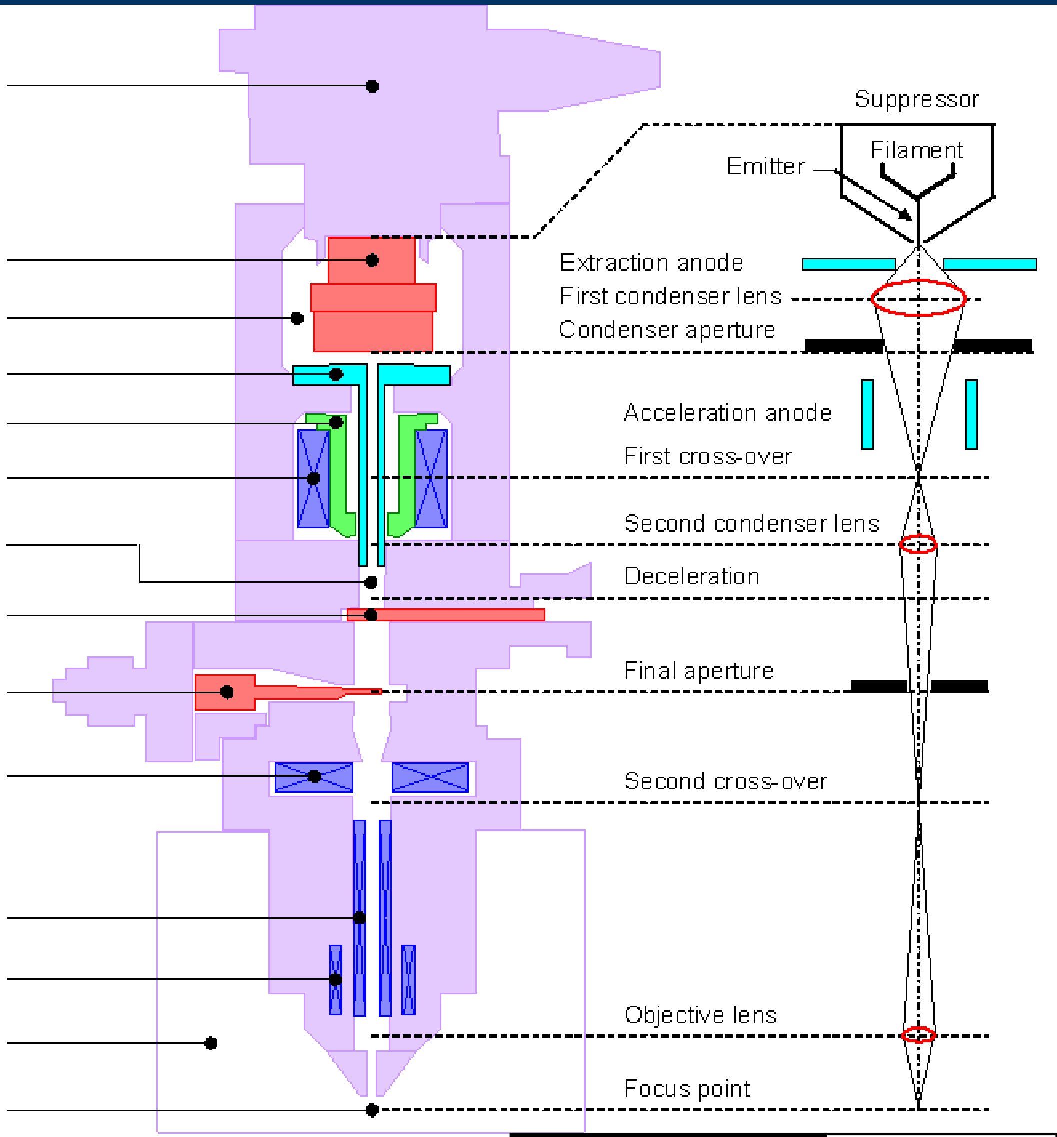
Intermediate lens

Scanning coils

Objective lens

Specimen chamber (p ~ 10^{-5} mbar)

Specimen mounted on a goniometric stage



Philips XL30 SFEG www.fei.com

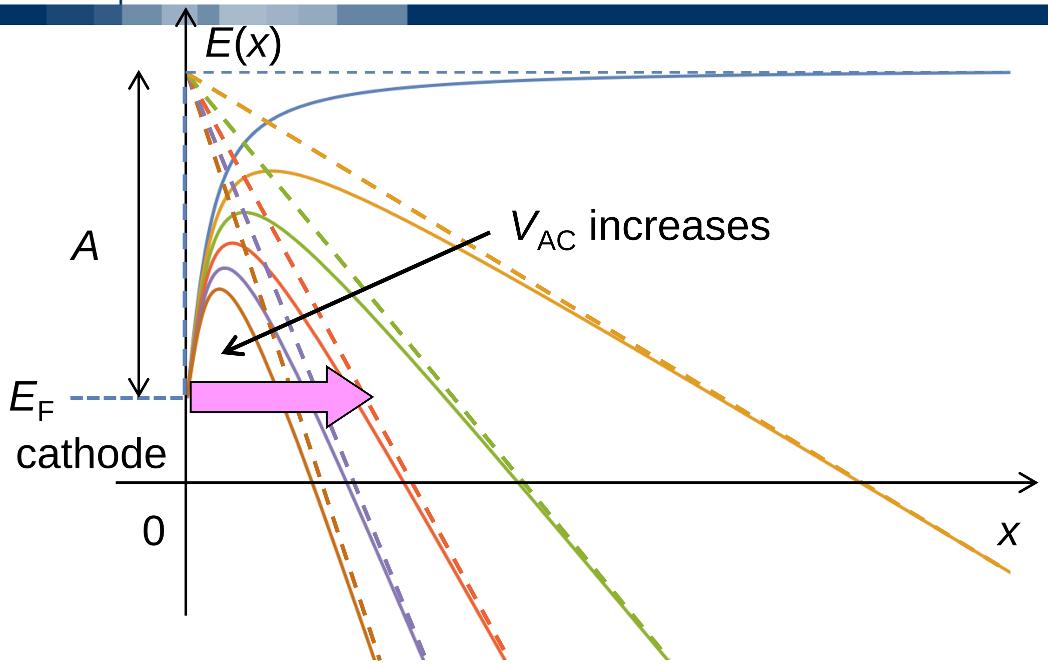
Electron Sources

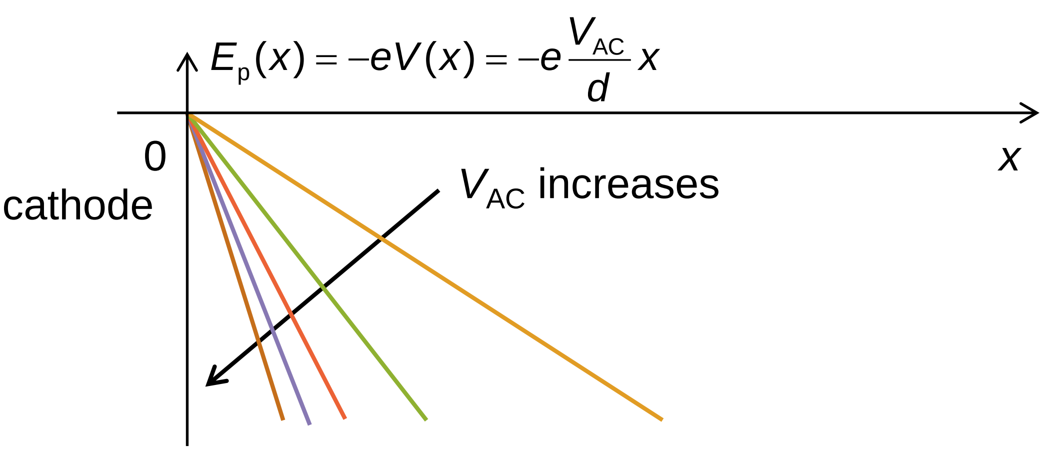
Tungsten hairpin	LaB_6 single crystal	Field Emission Gun
		

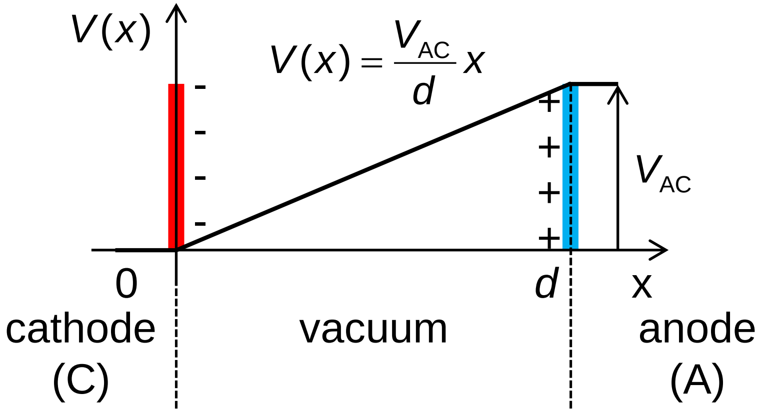
			Cold	Schottky
Source size	100 µm	10 µm	3 nm	10 nm
Temperature	2700 K	1300 K	300 K	1700 K
Emission	Thermionic	Thermionic	Field	Field/Sch.
Lifetime	100 hrs	1000 hrs	> 1 year	> 1 year
Required pressure	10^{-5} mbar	10^{-6} mbar	10^{-10} mbar	10^{-9} mbar
Price	30 €	1000 €	~ 5000 €	~ 5000 €
EBL	**NO**	**YES**	**NO**	**YES!**
	Poor resolution	**Good**	**Unstable**	**Excellent**

W melts at 3695 K

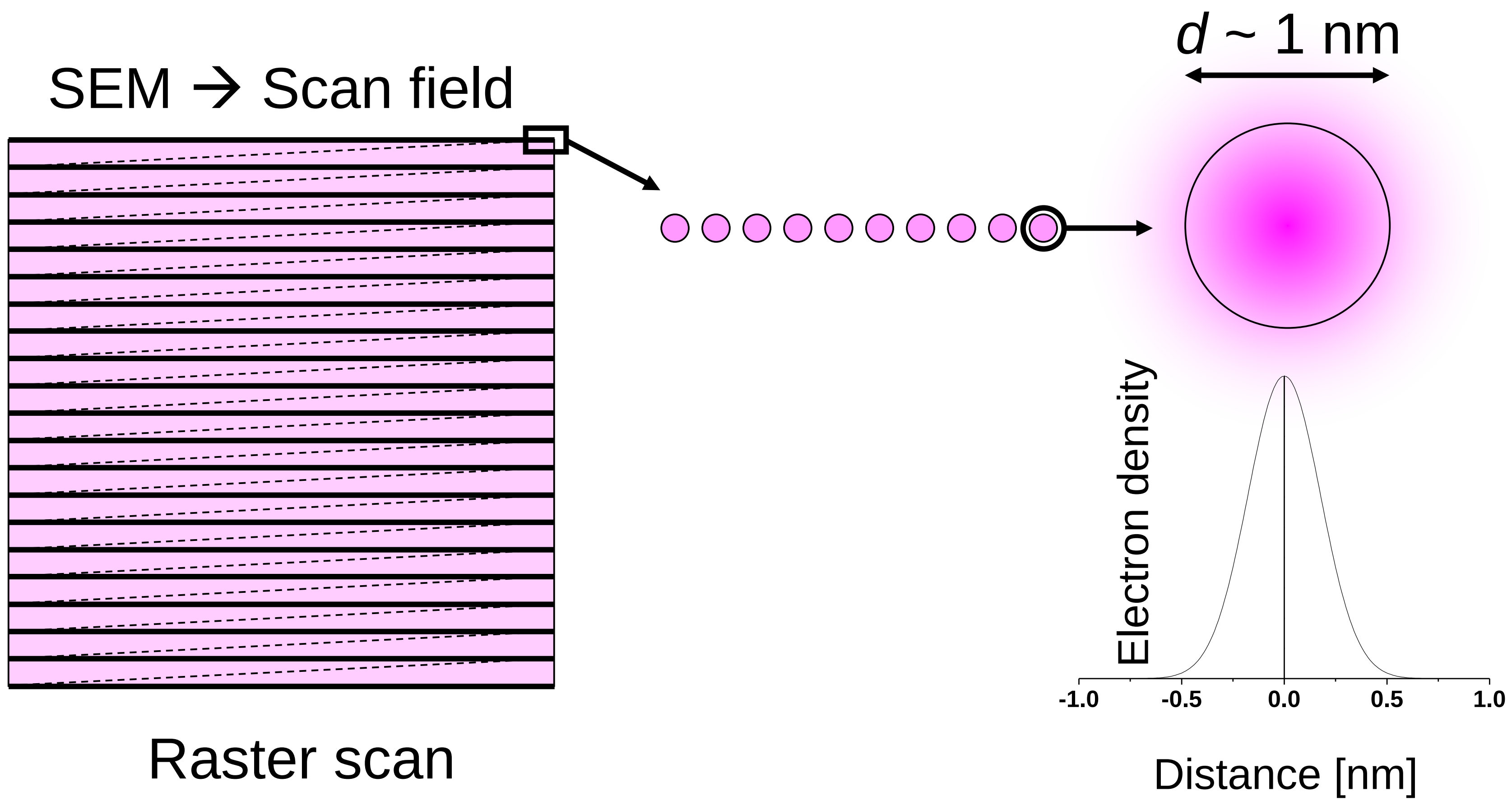
Schottky Effect





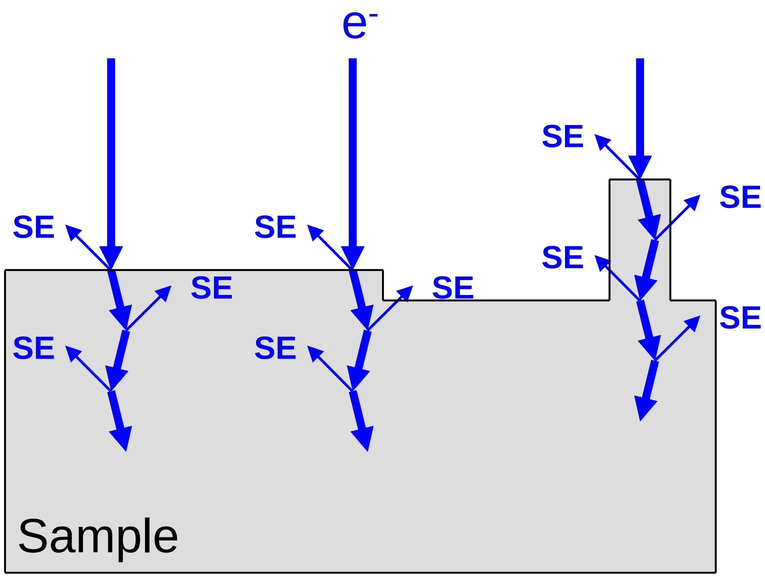


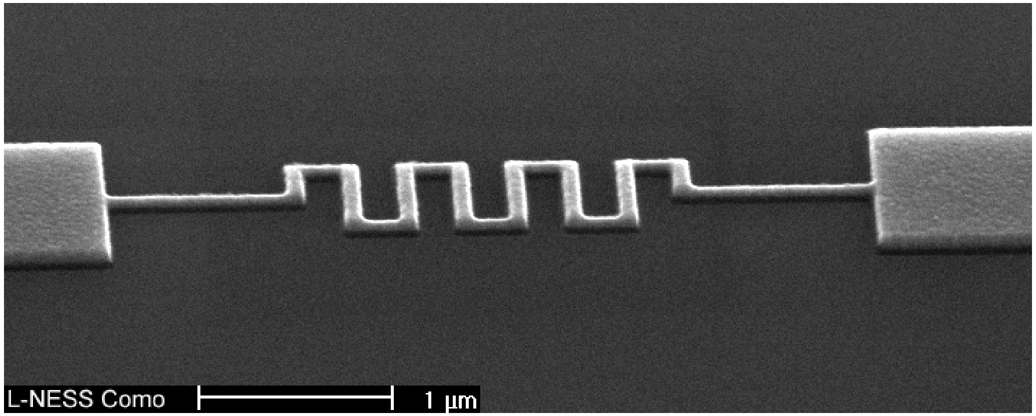
SEM: Indiscriminate Scan by Gaussian Spot



Detection of Secondary Electrons (SEs)

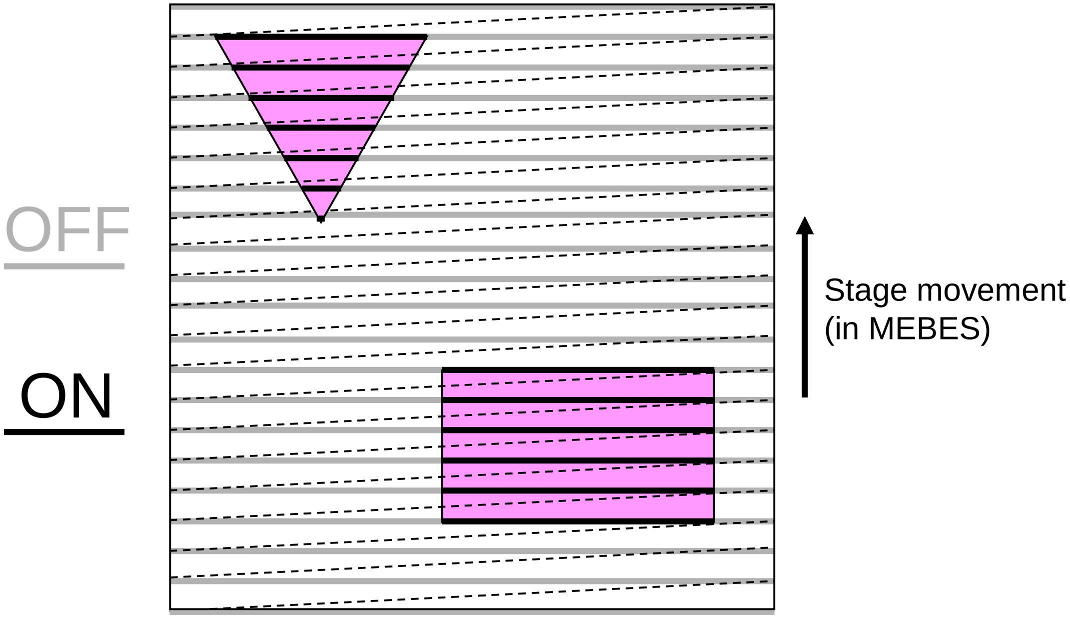
- Scanning and detection are in synchronism.
- Number of generated SEs depends on surface topography and material.



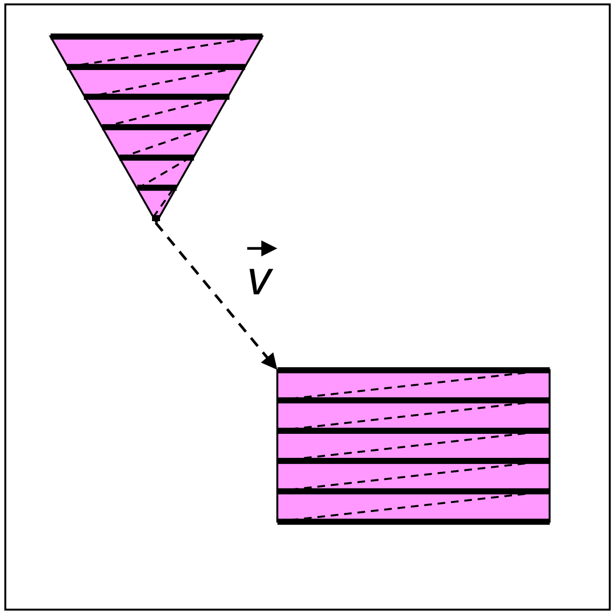


Exposure: Selective Scan by Gaussian Spot

EBL Writer → Write field | EBL Writer → Write field



Raster scan
Appl. Mat. (Etec) MEBES

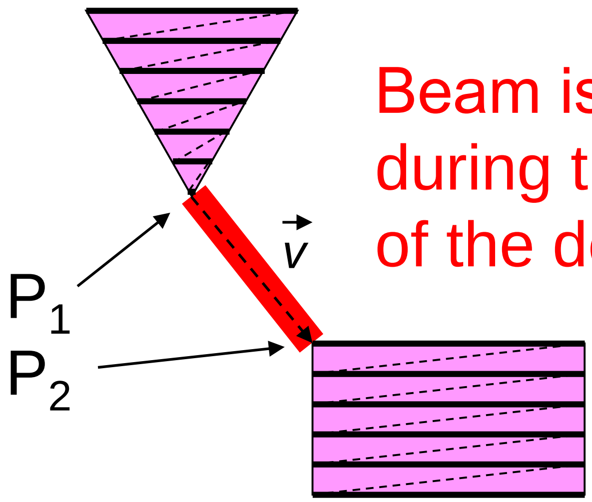


Vector scan (simplified)
Raith eLINE (6 nm)

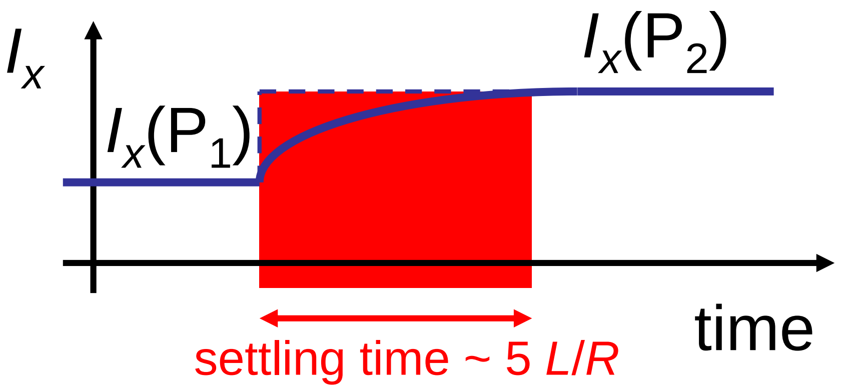
PC → Pattern generator → Deflection unit / Beam blanker

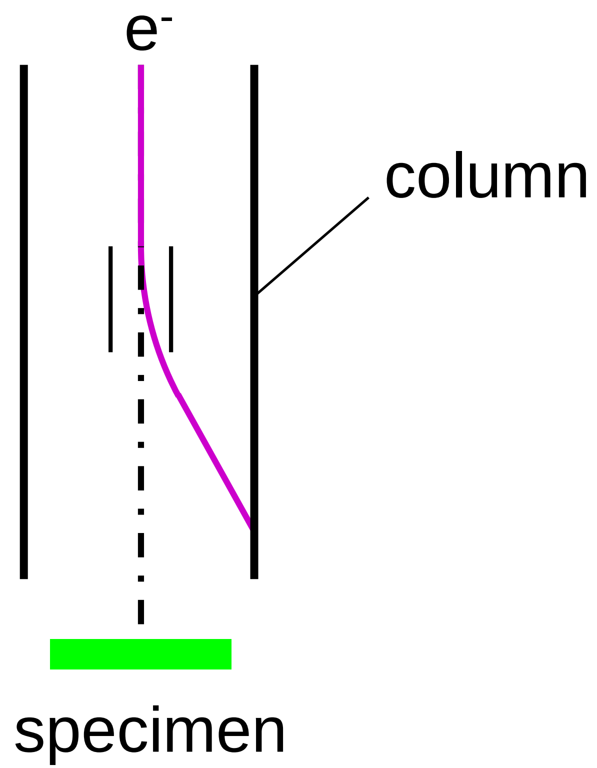
Beam Blanker

Fast (f > 10 MHz) electrostatic deflector (capacitor)

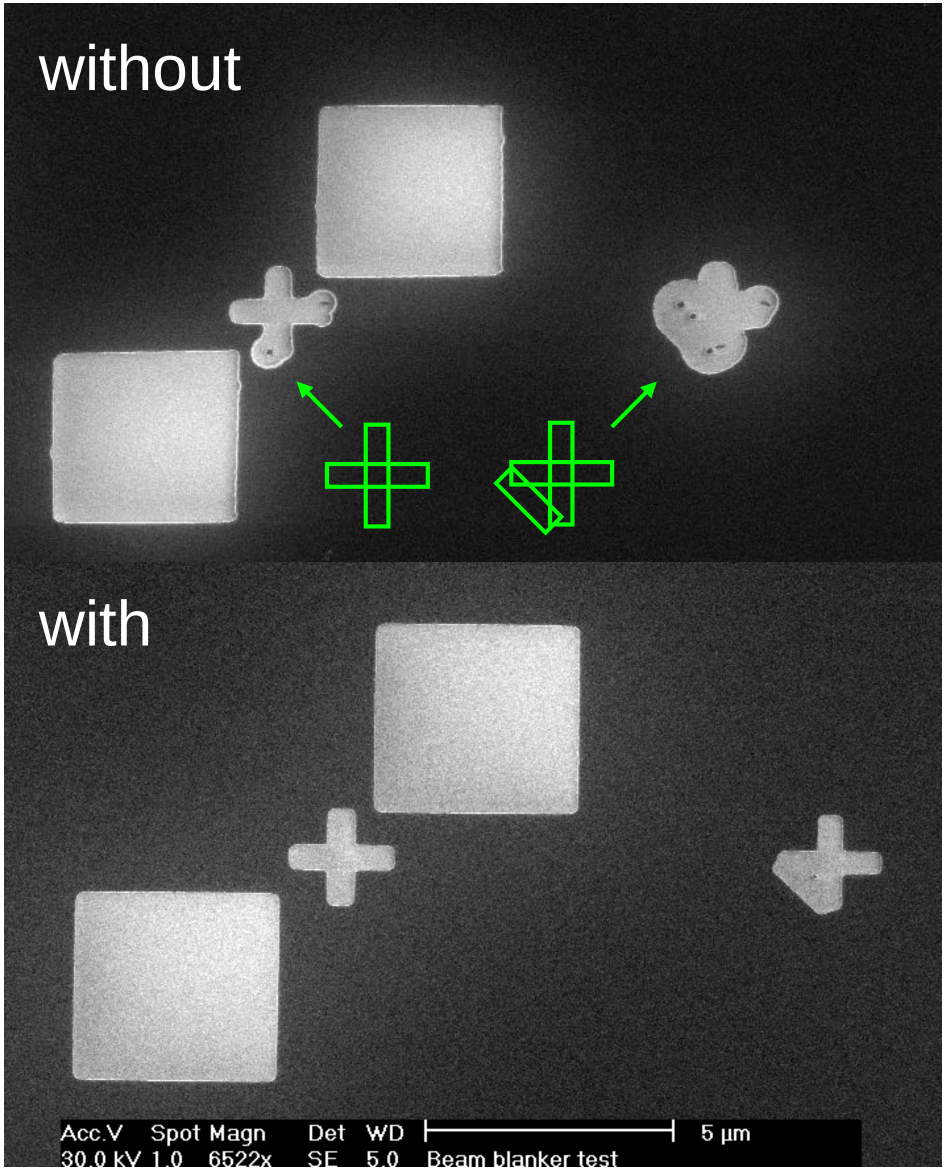


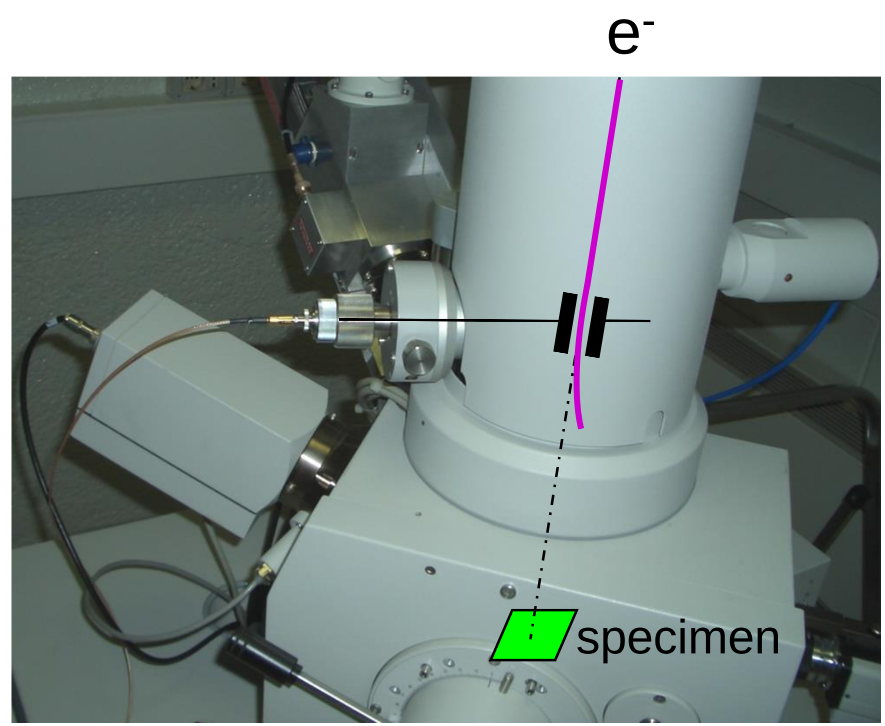
Beam is blanked (“OFF”) during the settling time of the deflection coils



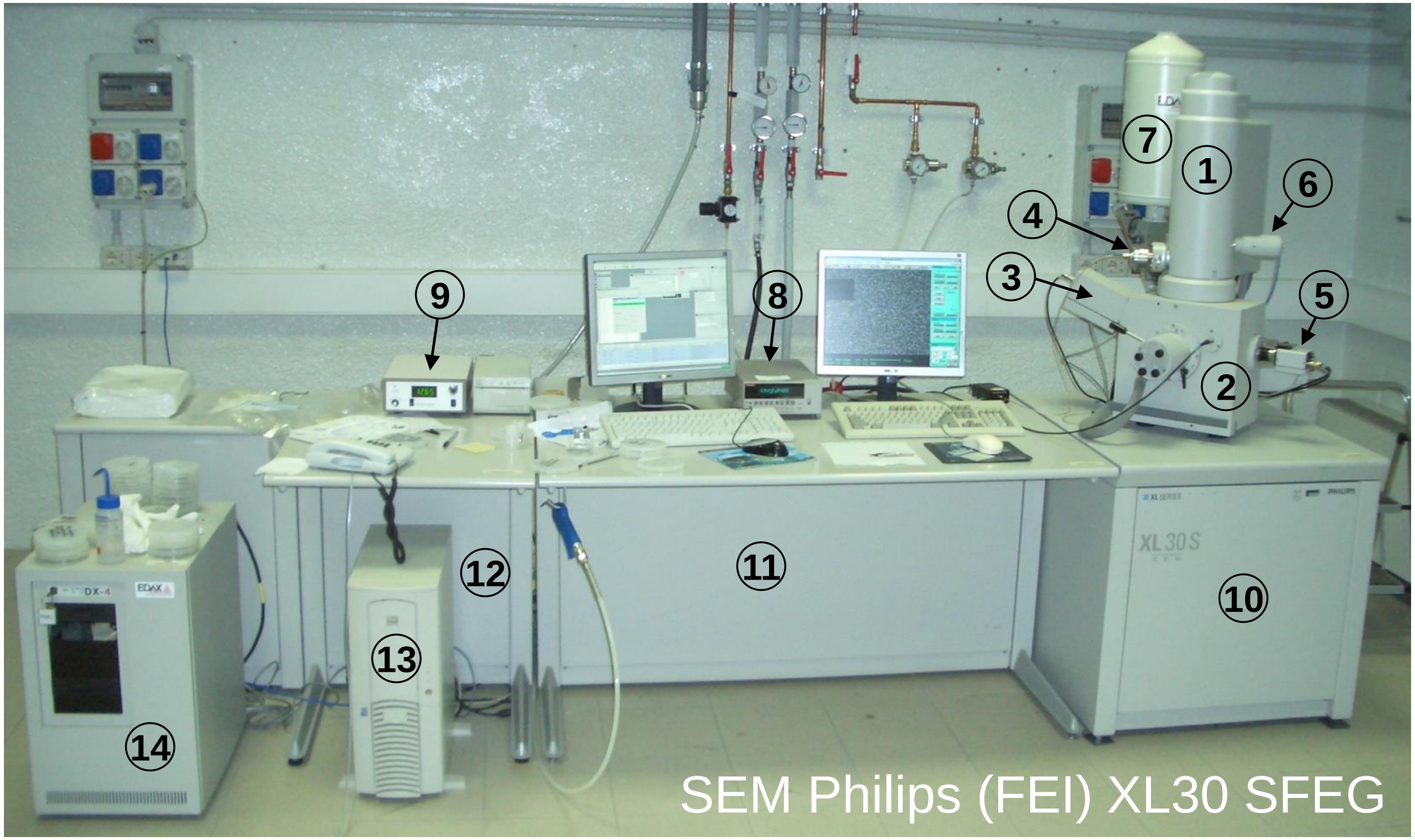


With and without Beam Blanker



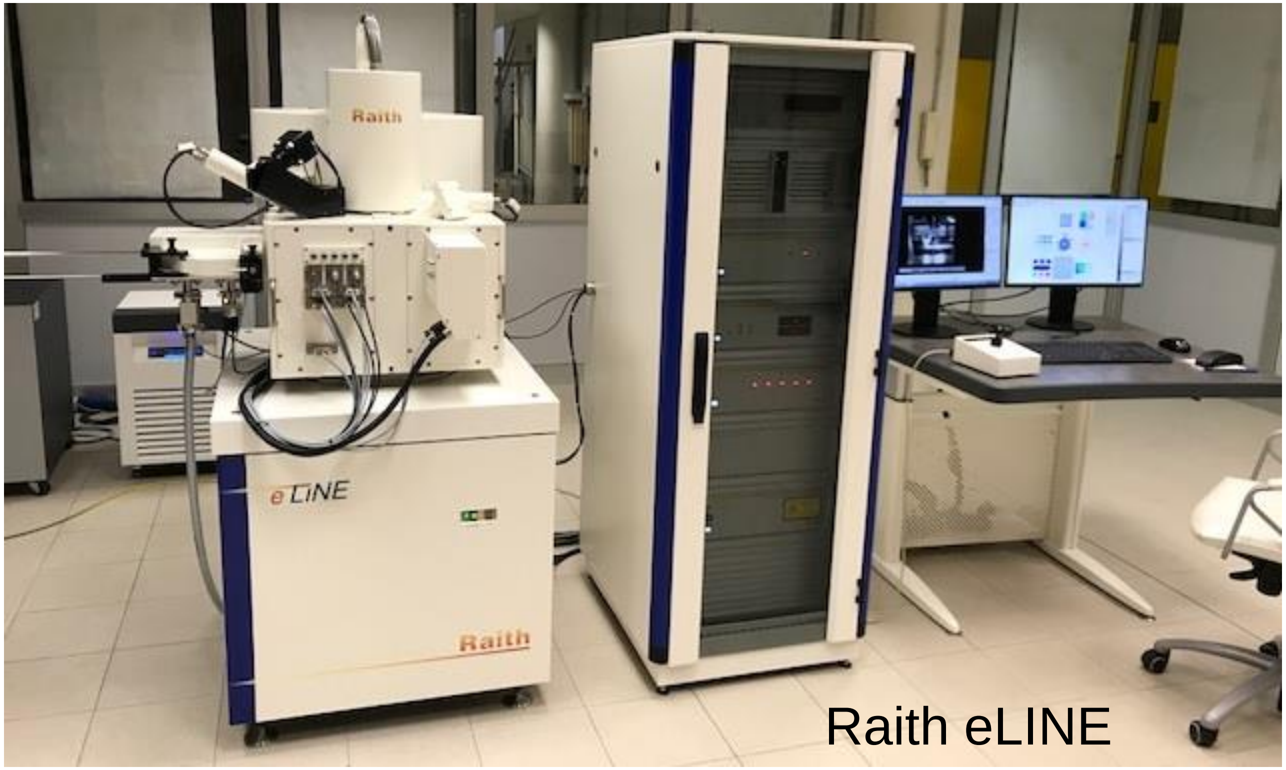


Old EBL System at L-NESS Como



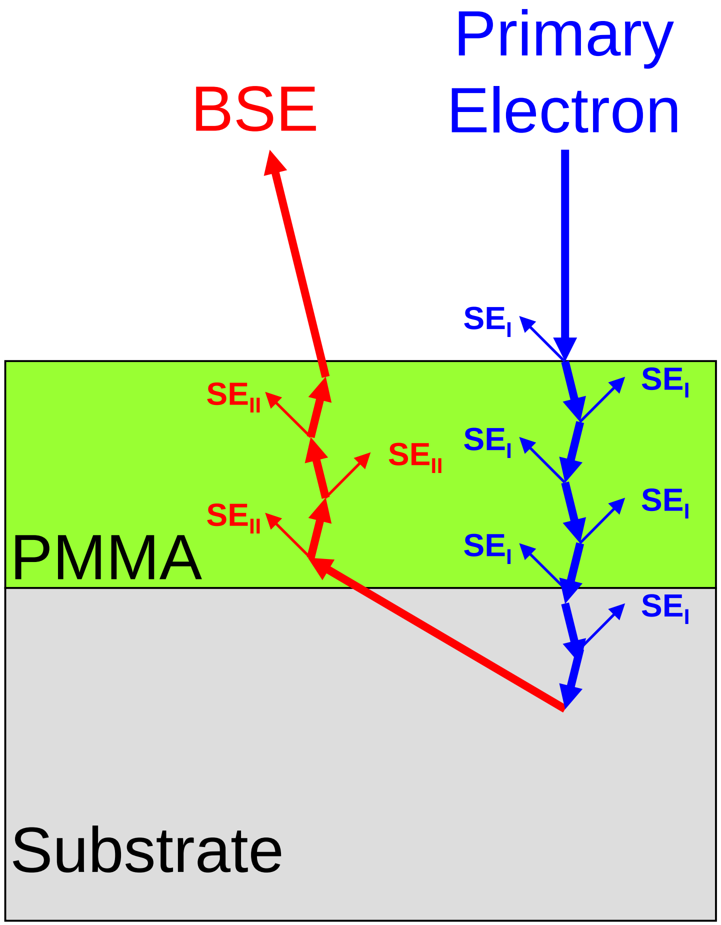
1. Column
2. Specimen chamber
3. Secondary electron detector
4. **Final aperture with integrated beam blanker**
5. CCD camera (to see the interior of the specimen chamber)
6. High tension valve
7. Liquid N_2 tank (for X-ray detector)
8. Pico-ammeter (to measure beam current)
9. Beam blanker power supply
10. Vacuum pumps and high tension circuitry
11. Electronics (printed circuits boards)
12. Power supply
13. **Lithography PC (Raith Elphy Quantum)**
14. SEM PC with integrated X-ray analyzer

New EBL System at L-NESS Como

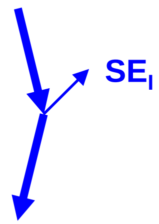


Raith eLINE

1. Schottky field-emission gun
2. Acceleration voltage up to 30 kV
3. High-speed pattern generator (20 MHz)
4. Laser interferometer stage with a stitching error < 20 nm and 100 x 100 mm horizontal and 30 mm vertical travel range under full interferometric control
5. Alignment error < 20 nm
6. Automated laser height sensing (working distance error < 5 μm)
7. Traxx module for stitching error free continuous writing mode for elongated paths (fixed-beam moving stage mode - FBMS)
8. Manual load-lock

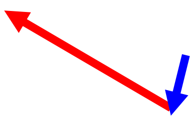


Forward scattering



- Frequent
- Small angle inelastic scatt.
- Generation of SE
- E_{SE} < 50 eV

Backward scattering



- Occasional
- Large angle elastic scatt.
- E_{BSE} ~ E ~ 30 keV

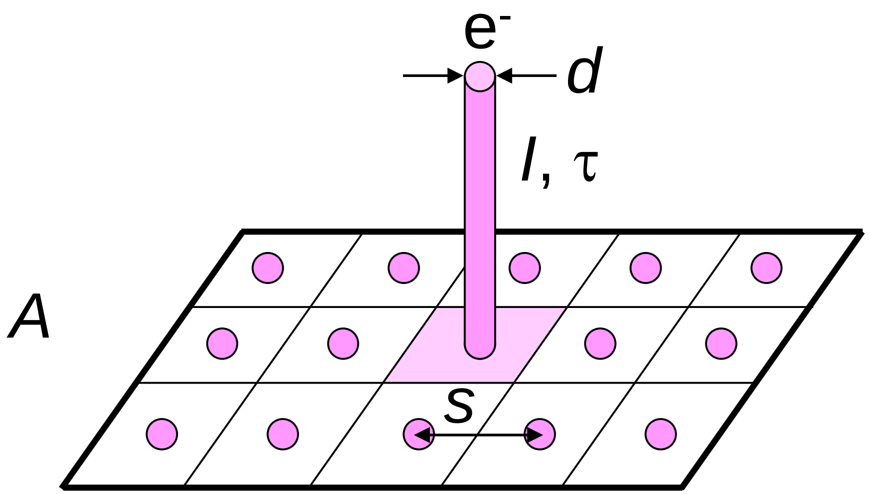
Resist exposure mostly from SE

Proximity Effect

SE = Secondary Electron

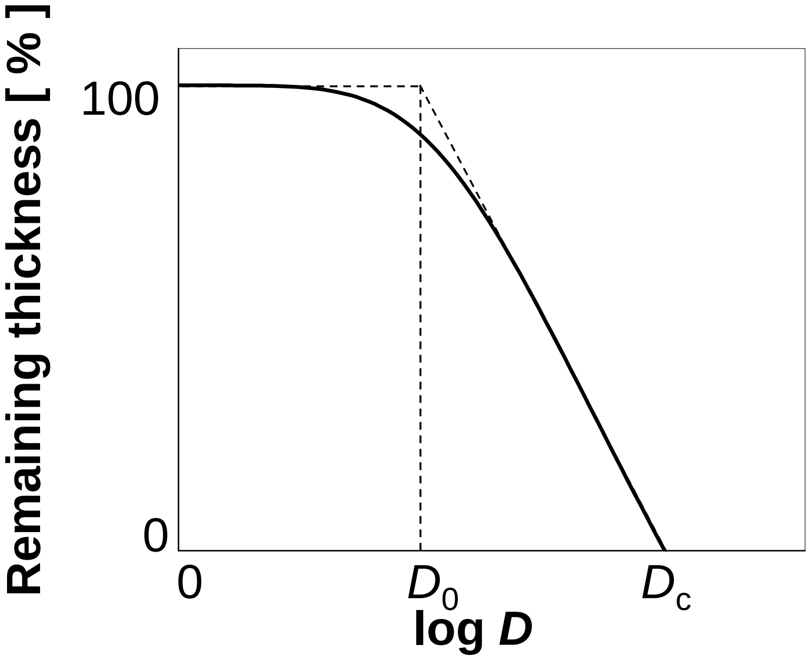
BSE = Back Scattered Electron

Primary Electron Dose (*D*)



$$D = \frac{Q}{s^2} = \frac{I\,\tau}{s^2}$$

s = step size
τ = dwell time
I = beam current
d = beam diameter

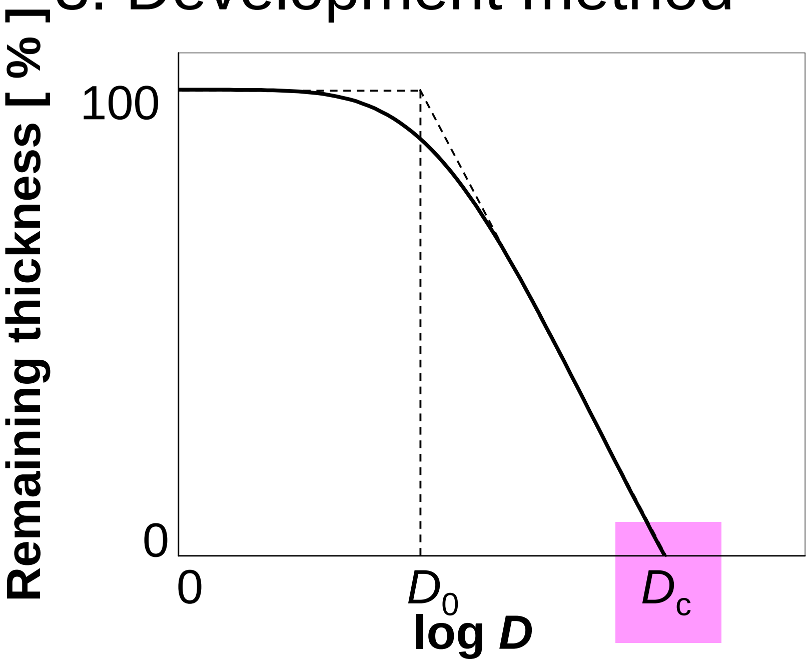


Sensitivity = 1 / D_c
Contrast = γ = 1 / log(D_c/D_0)

Perfect resist: S → ∞, γ → ∞

Clearing Dose

- Independent of the resist thickness (more SEs generated in thicker resist)
- Depends on:
  1. Beam energy - Bethe formula: $dE\,/\,dz \propto -1/\,E$
     High energy electrons scatter less → less SEs generated
  2. Resist type
  3. Development method



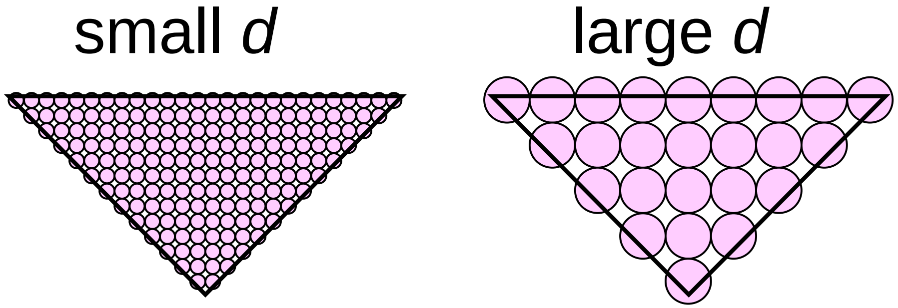
$D_{c,PMMA}$ [μC/cm^2] ~ 10 x E [keV]

Exposure Strategy

User chooses *I* and *s* → patt. gen. calculates required $\tau = \dfrac{D\, s^2}{I}$

High resolution: *I* and *s* as small as possible

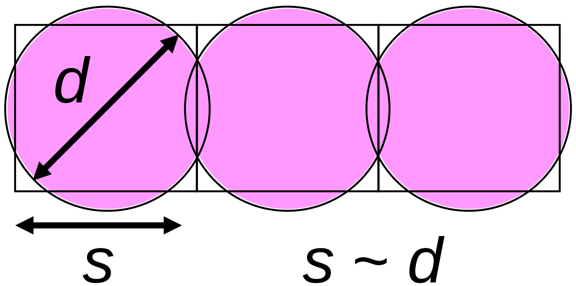
- Choice of beam current *I* (i.e., beam diameter *d*):



$CD > 10\, d$

XL30 SFEG:
d ~ 2 nm for *I* ~ 21 pA

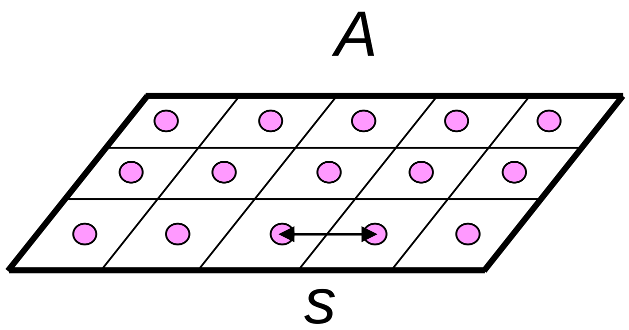
- Choice of step size *s*:



Exposure Time

20. Find expression for exposure time *T.*

$$T = \frac{A}{s^2}\,\tau = \frac{D\,A}{I}$$

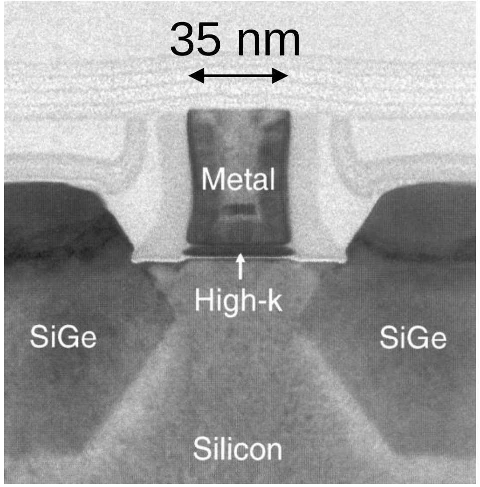


21. Calculate exposure time of gates in Intel Tukwila µP in the EBL system in Como.

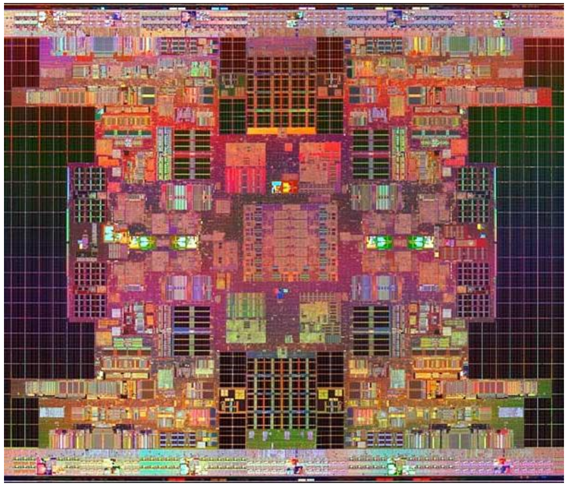
$A \sim 35$ nm × 1 µm = $3.5 \cdot 10^{-14}$ m^2
D_c = 300 µC/cm^2 = 3 C/m^2 (PMMA)
I = 21 pA (Como)

T = 5 ms
$T_{\mu P} = 2 \cdot 10^9 \cdot 5$ ms = 116 days !

5 ms



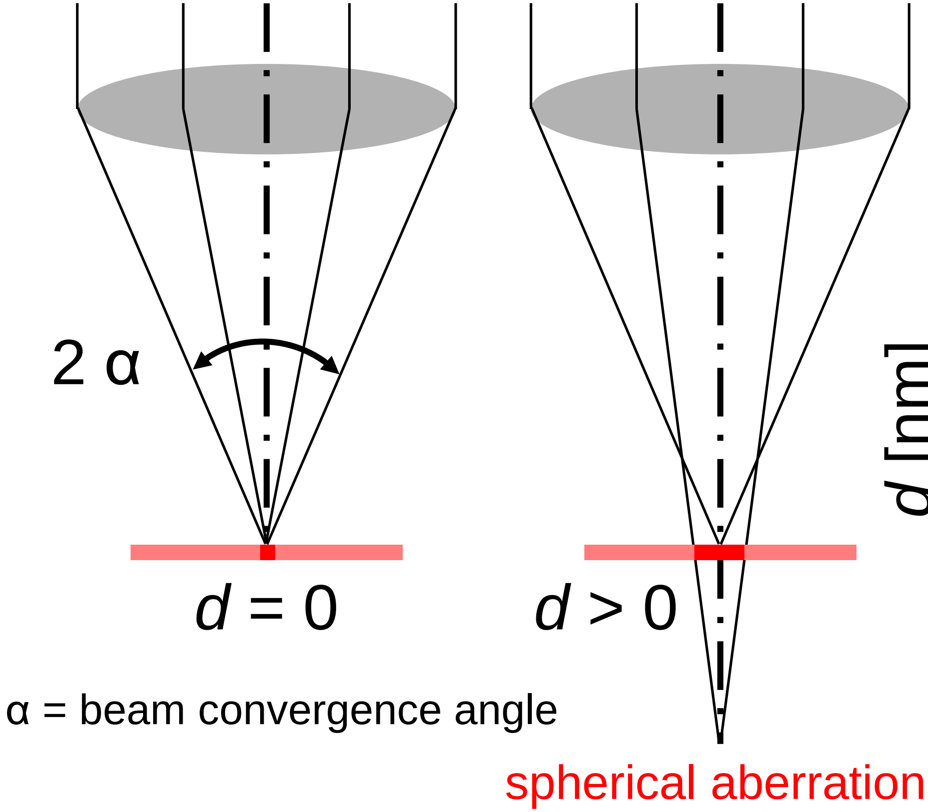
116 days

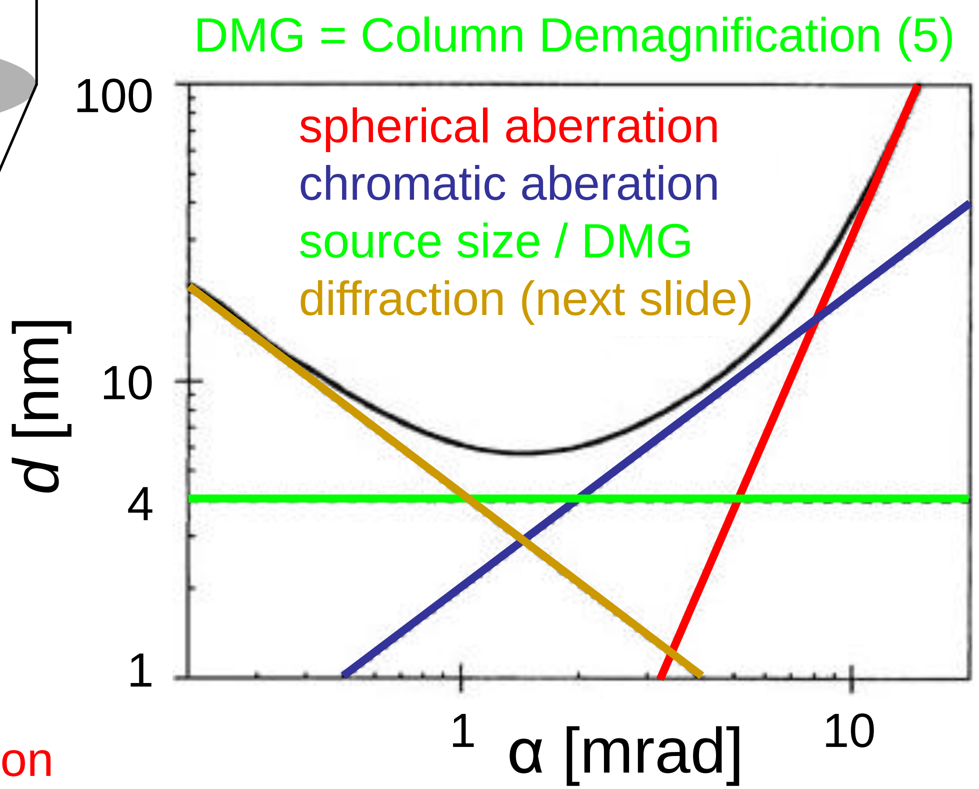


Resolution Limit: Beam Diameter *d* (Spot Size)

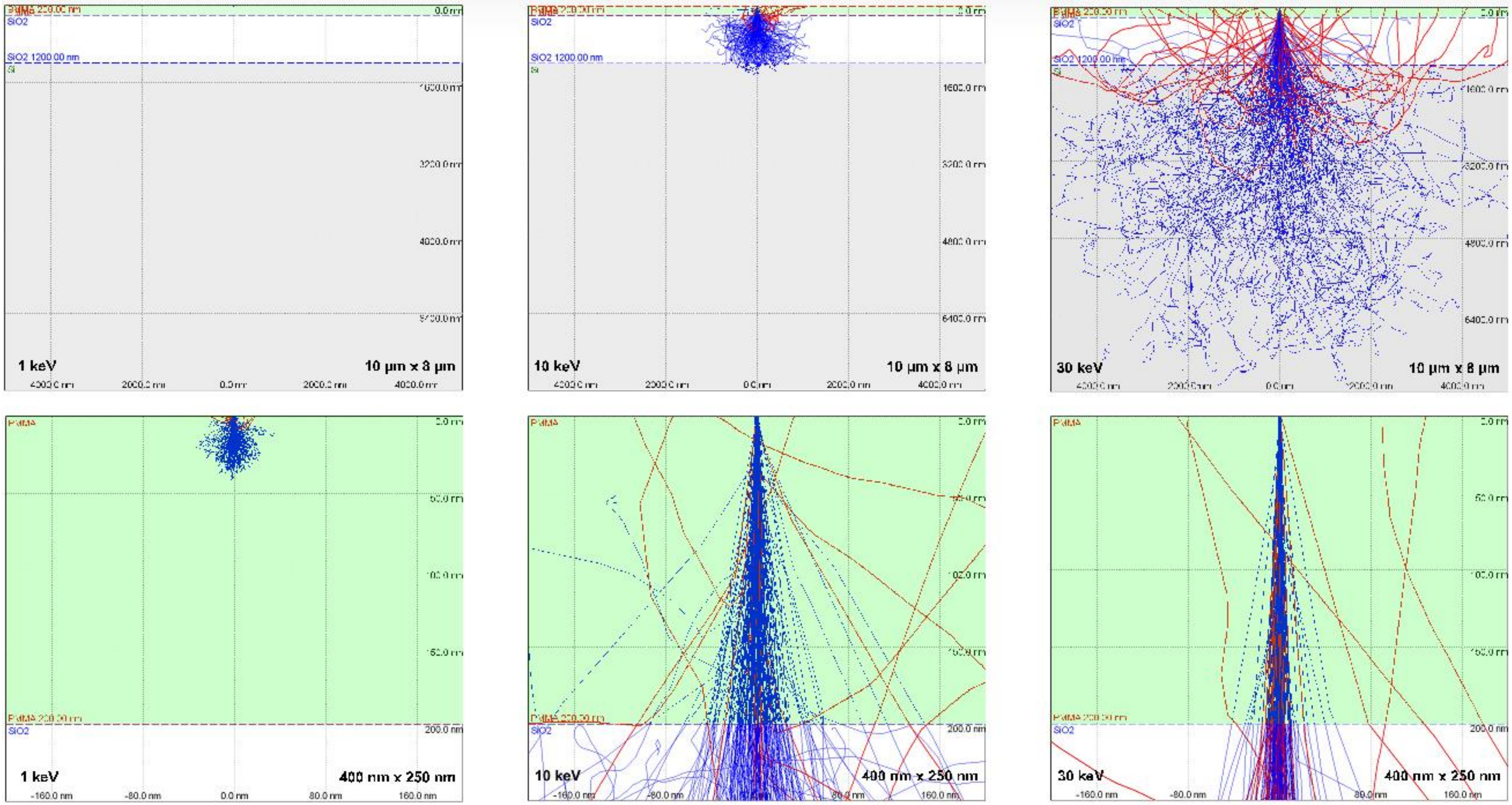
- Electron wavelength (diffraction) is not a limiting factor
  λ = 0.01 nm at E = 20 keV ($\lambda \propto E^{-1/2}$)

- Imperfections in the electron optics are the main limiting factor





Influence of Electron Energy

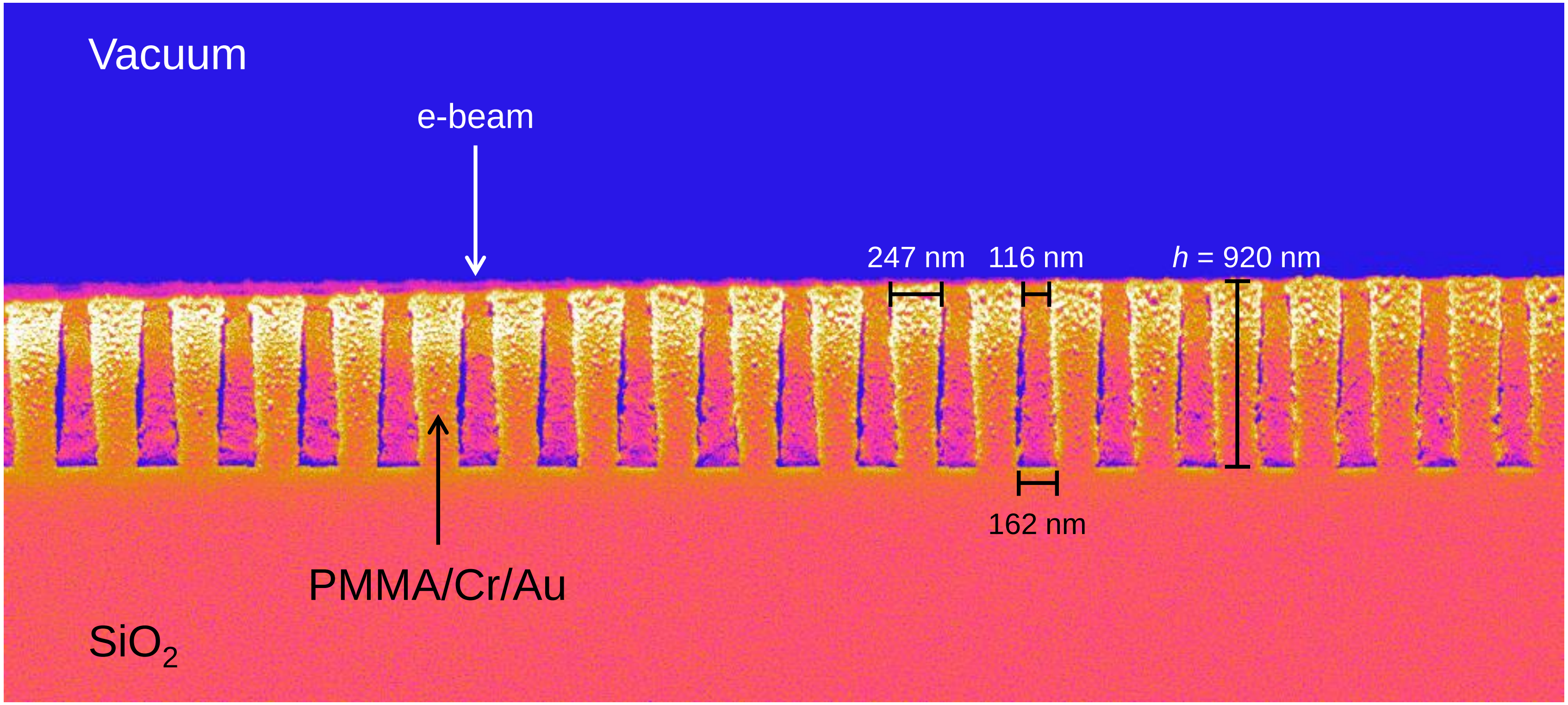


1 keV | 10 keV | 30 keV

High Resolution → High Energy + Thin Resist

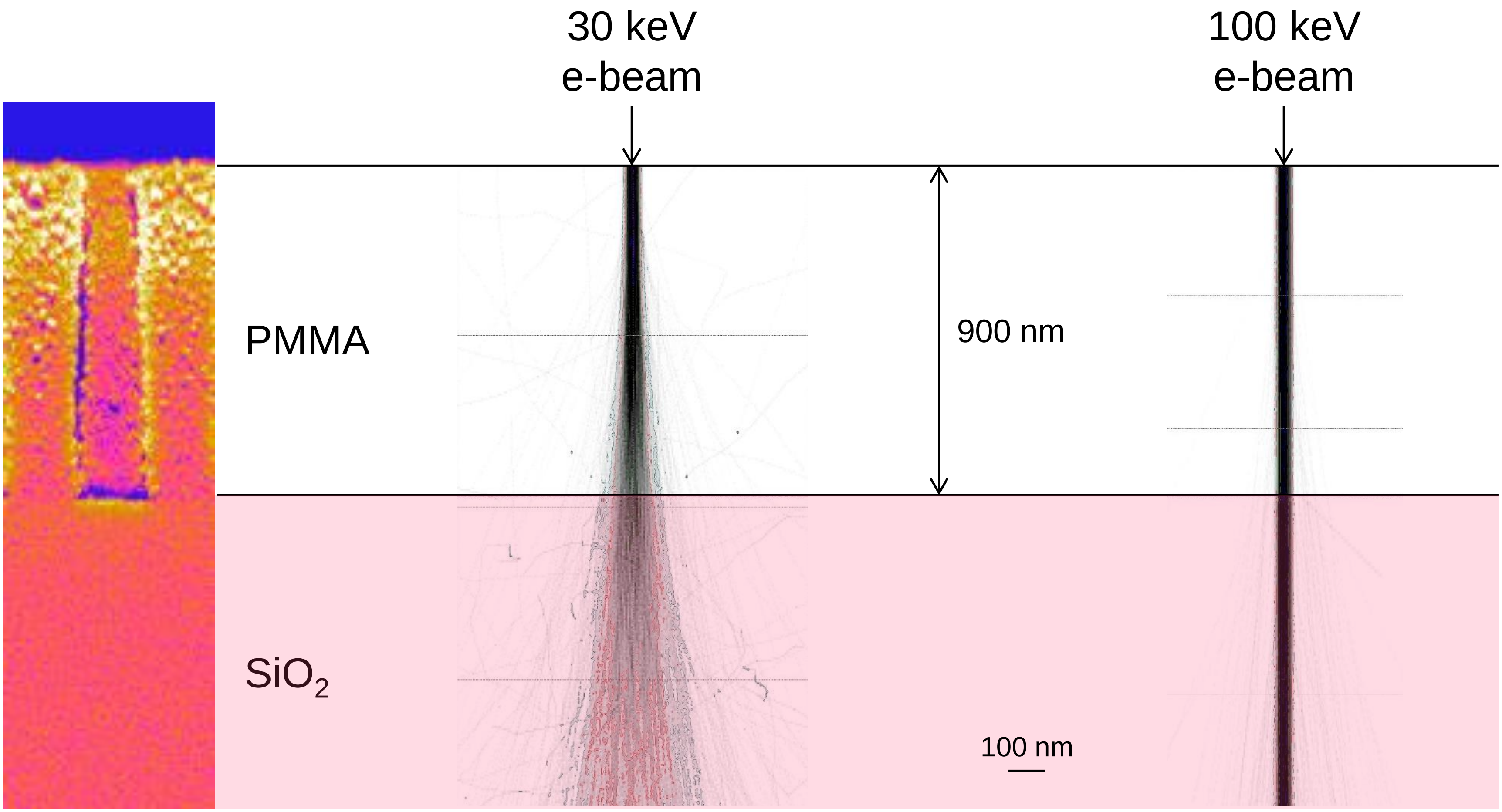
CASINO www.gel.usherbrooke.ca/casino

Exposure of Thick Resist



- Pillars are rough because of the evaporated Cr/Au (10/10 nm) film, which was used to prevent charging during SEM imaging.
- The inhomogeneity of the width of the holes (they are wider at the bottom) is due to forward electron scattering in a 900-nm-thick PMMA resist.

30 vs. 100 keV Beam

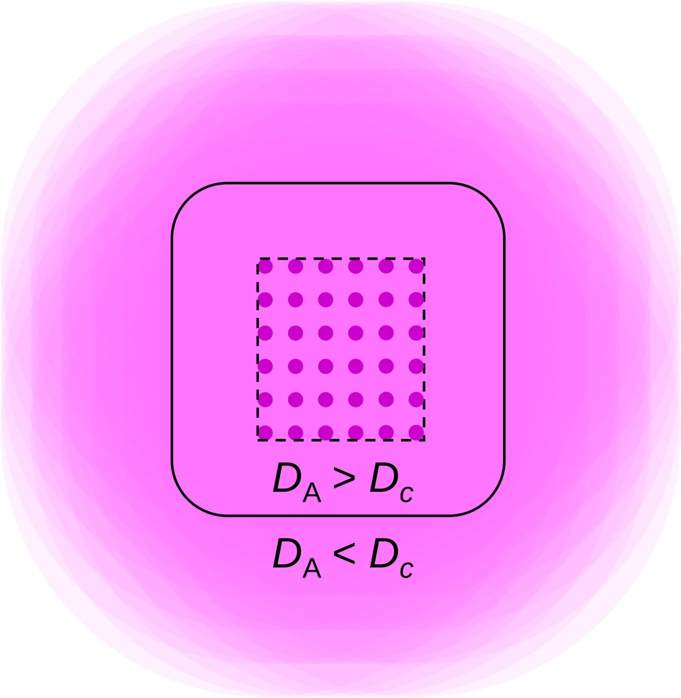


- The example shows exposure of a 50-nm-wide feature at two different beam energies (30 and 100 keV)

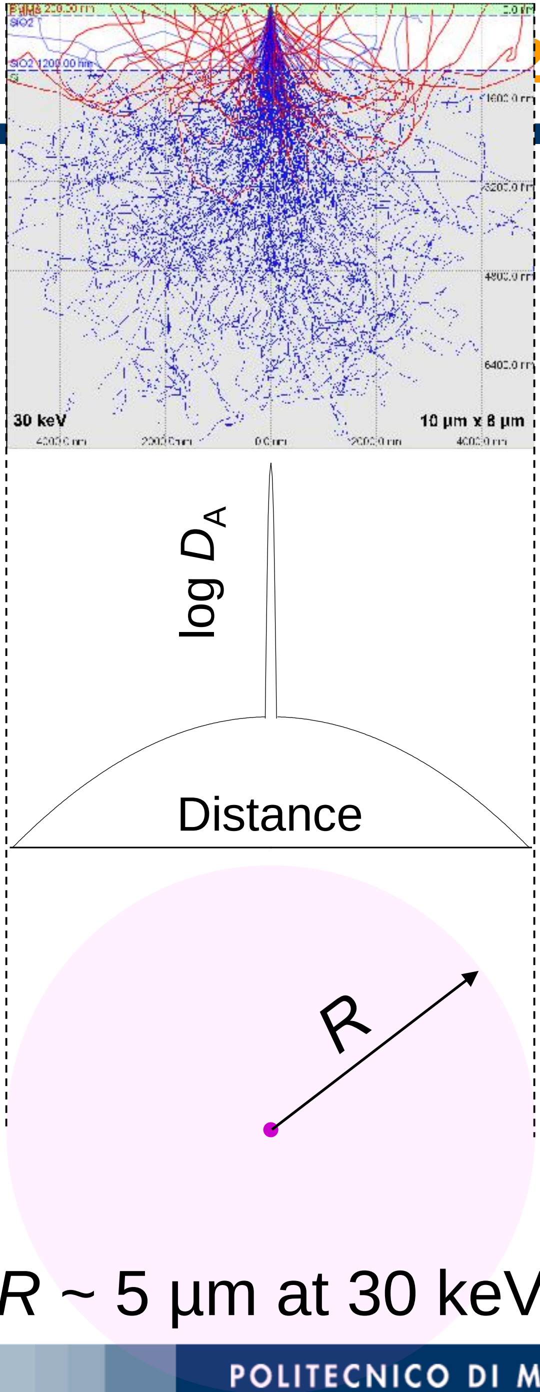
Proximity Effect

Unwanted exposure by BSE

Absorbed Dose (D_A) > Primary Dose (D)

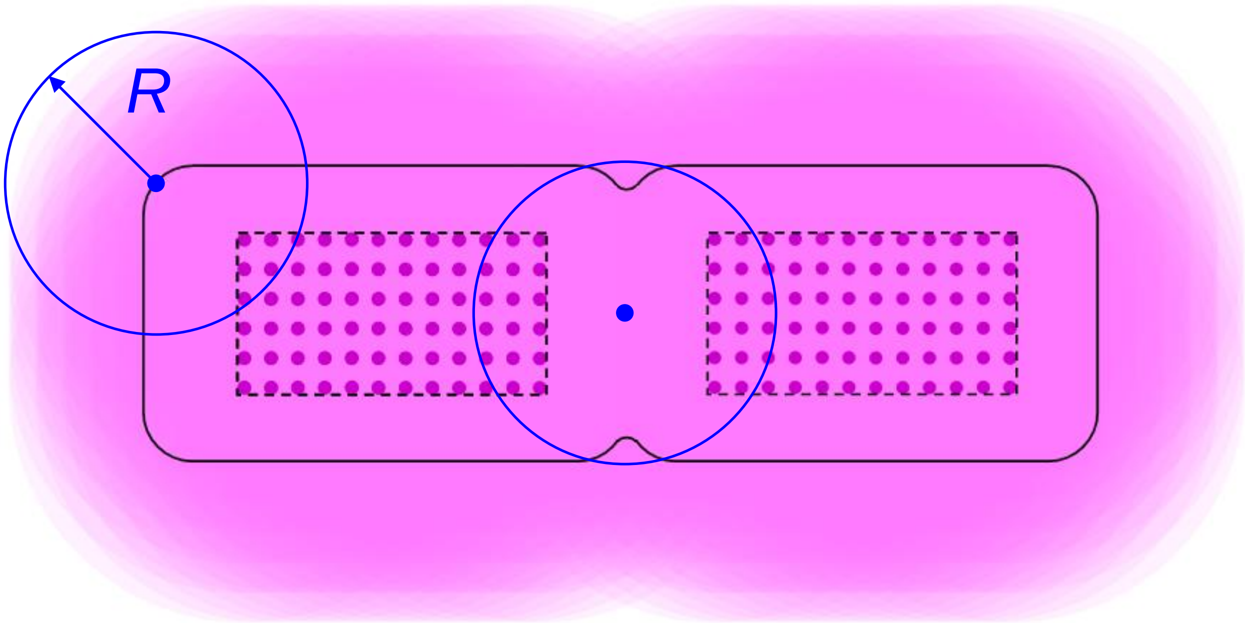


Another resolution limiting factor



R ~ 5 µm at 30 keV

Proximity Effect – Several Objects

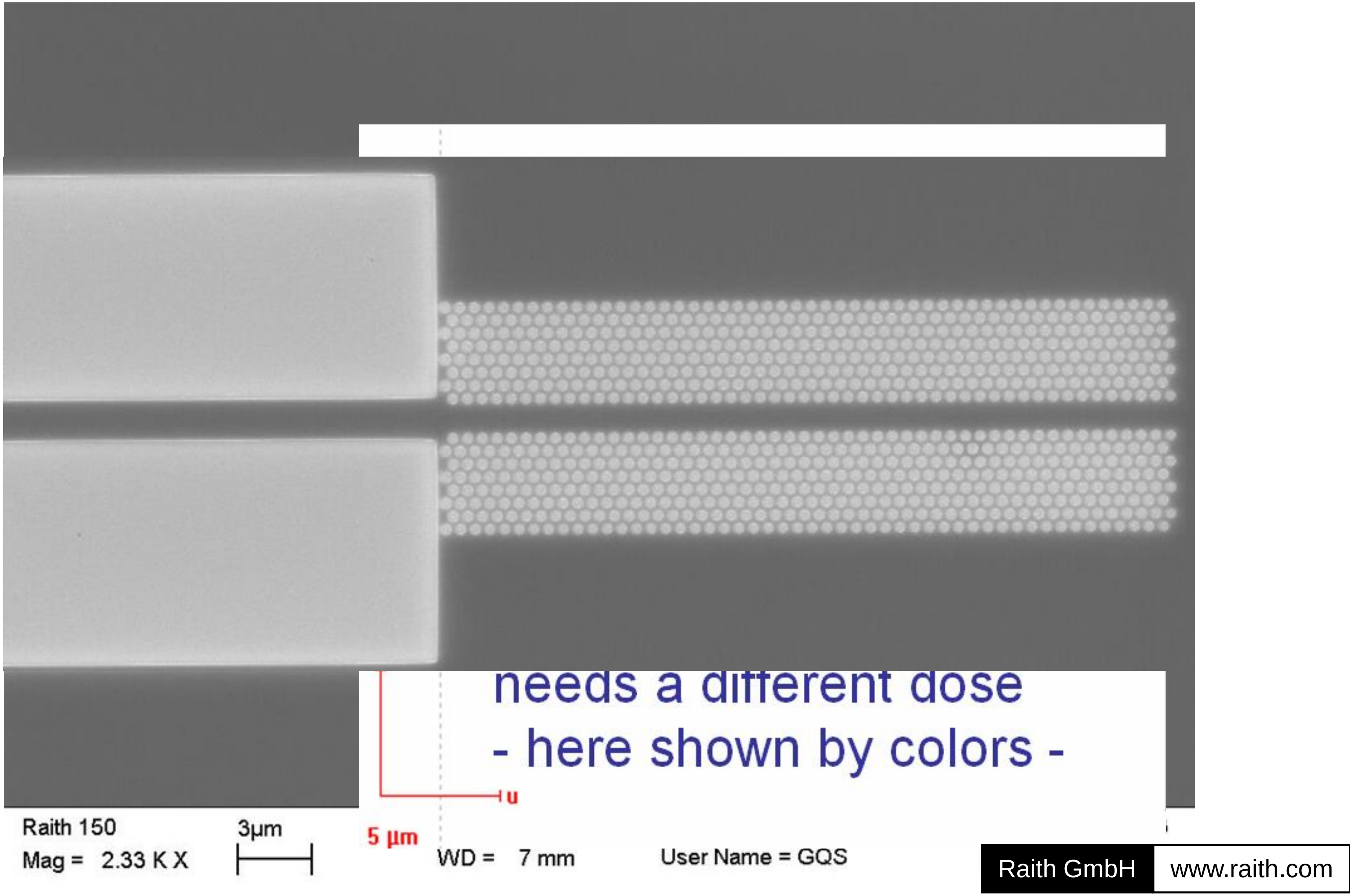


- Objects get connected
- Absorbed BSE dose depends on the pattern

Workaround: Use too low *E* (< 5 keV) or too high *E* (100 keV)

Too low *E*	Too high *E*
Resolution	Expensive systems
Thin resist	Sample damage
Aberrations	Heating

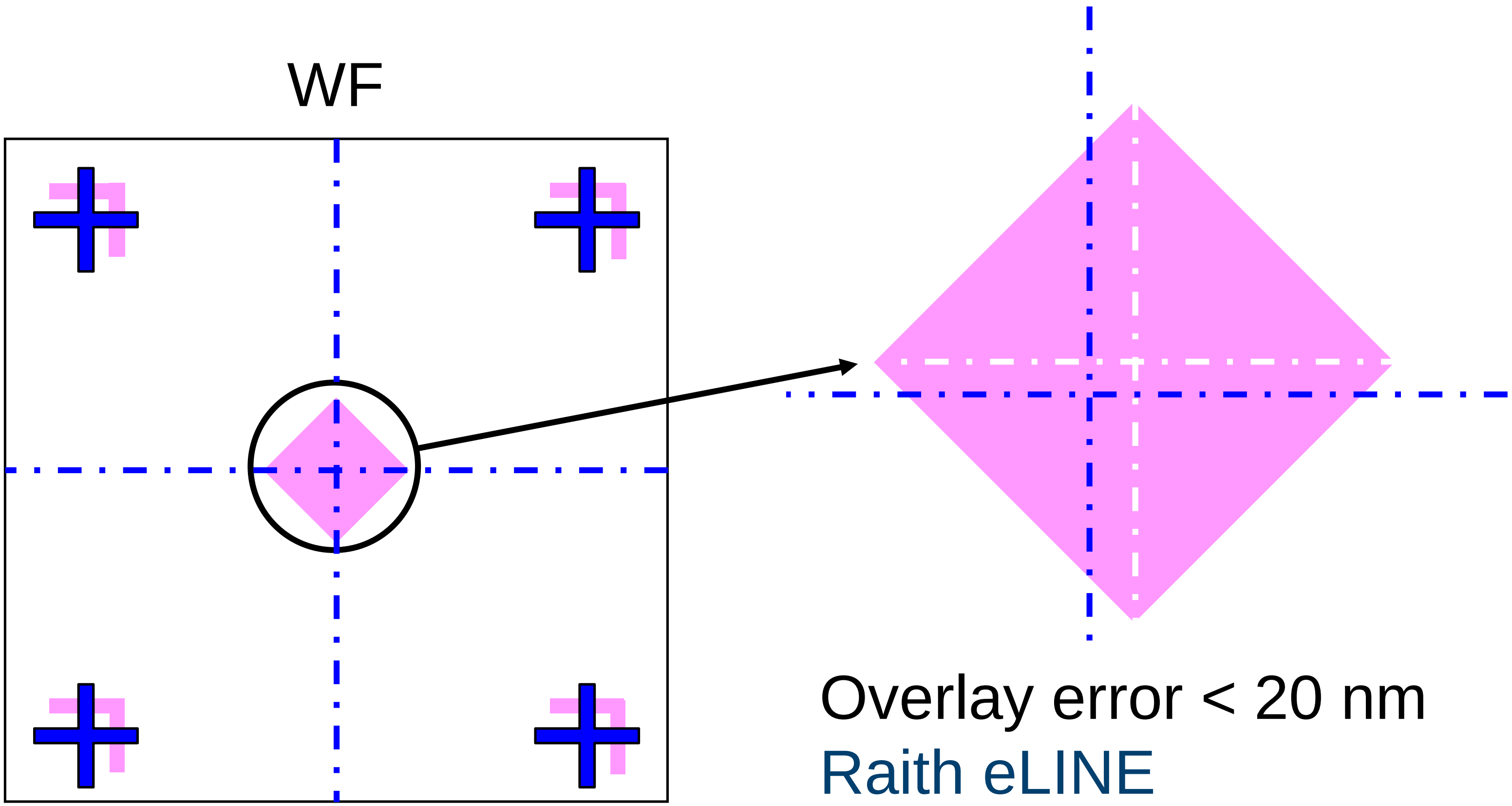
Proximity Effect Correction: Dose Modulation



Overlay Accuracy

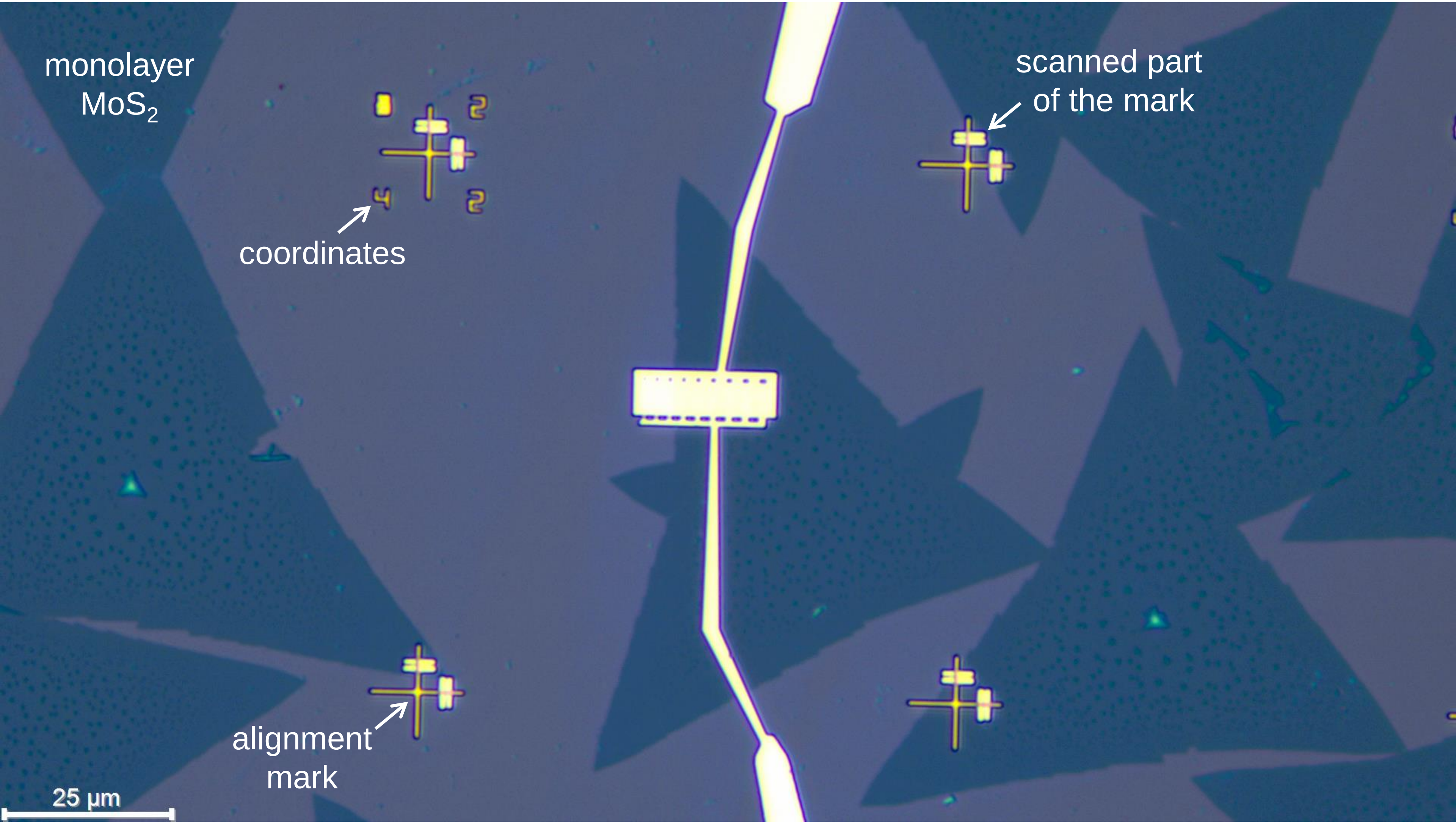
What if several fabrication steps have to be overlaid?
A single MOSFET requires at least 4 different steps.

Steps (WFs) are aligned with respect to alignment marks.



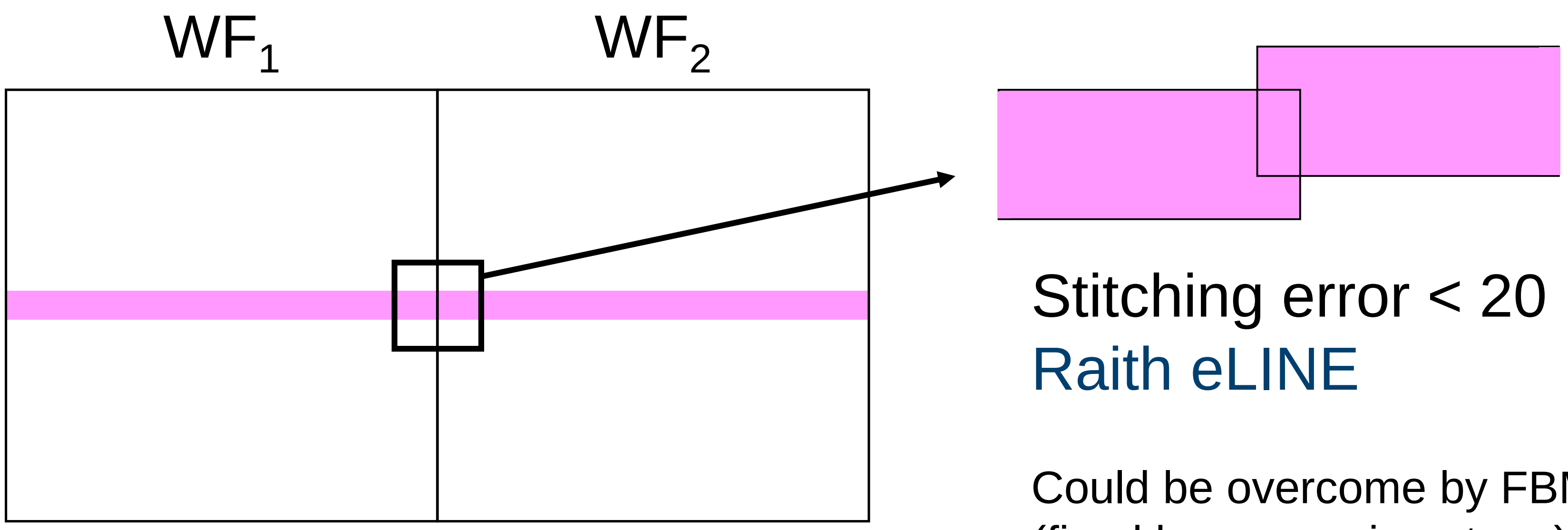
Overlay error < 20 nm
Raith eLINE

Overlay Procedure



What if the write field is smaller than the pattern size?
High resolution WF_{max} ~ 1 mm
Intel Tukwila die size = 21.5 mm × 32.5 mm

1. The pattern is divided into several WFs.
2. Each WF is centered with respect to the central axis by a laser interferometer stage.



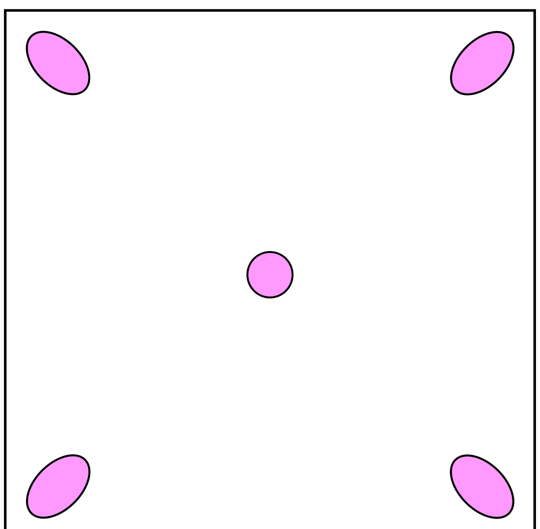
Stitching error < 20 nm
Raith eLINE

Could be overcome by FBMS (fixed beam moving stage)

Dedicated EBL Systems (Vector Beam)

Very expensive (price starts at 1.5 M€). Why?

- Operate at much higher energies (100 keV).
- Ultra fast pattern generator (125 MHz)
- Long term beam current stability.
- High resolution even at very large WFs (~ 1 mm) and beam currents (> 1 nA).
- Very small stitching and overlay errors.
- Dynamic focus and astigmatism corrections.



Raith EBPG 5200

Reactive Ion Etching (RIE)

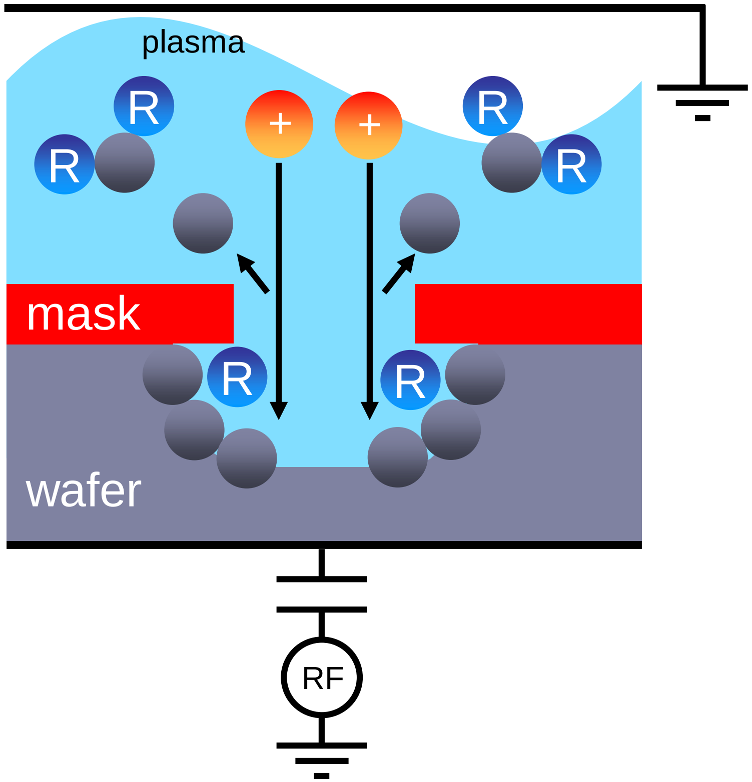
Chemical etching: plasma is created by accelerating electrons in an AC electric field (f = 13.56 MHz). Oscillating electrons hit precursor molecules ionizing them (mostly $CF_4 + e^- \rightarrow CF_3^+ + \mathbf{F} + 2e^-$) and creating sustainable plasma.

Electrons accelerate in AC field while heavy ions do not. Oscillating electrons which hit the upper platter or chamber walls are fed to ground. Electrons which hit the wafer build up negative charge (~ – 100 V) due to DC isolation of the wafer. Established electric field attracts positive ions toward the wafer.

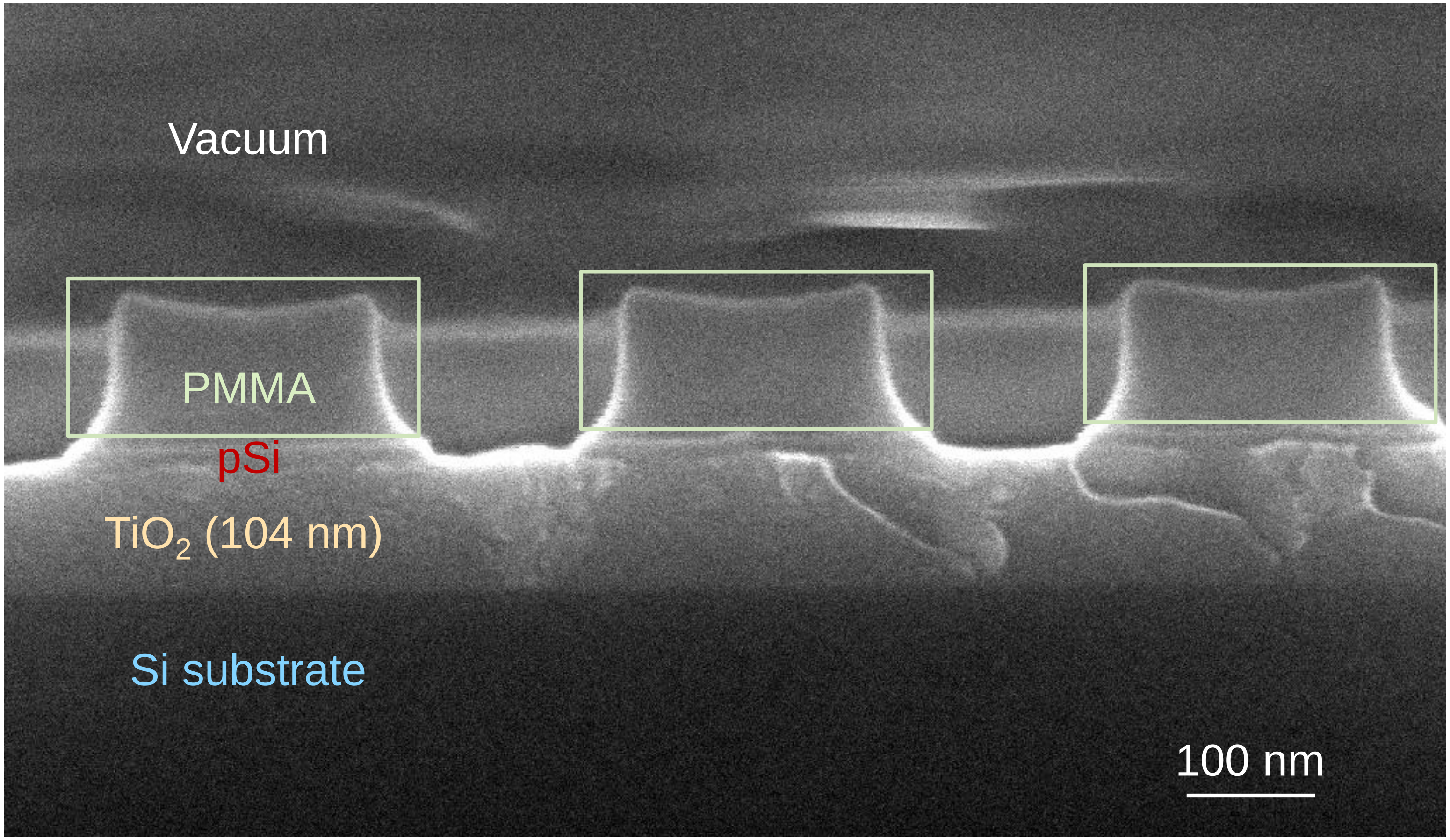
Physical etching: accelerated ions knock of some material by momentum transfer (sputter etch) → anisotropic etch.

Ion bombardment allows easier penetration of radicals which increases the etch rate.

The degree of anisotropy is tuned by balancing chemical and physical components of etching.



Etching of Thin Materials

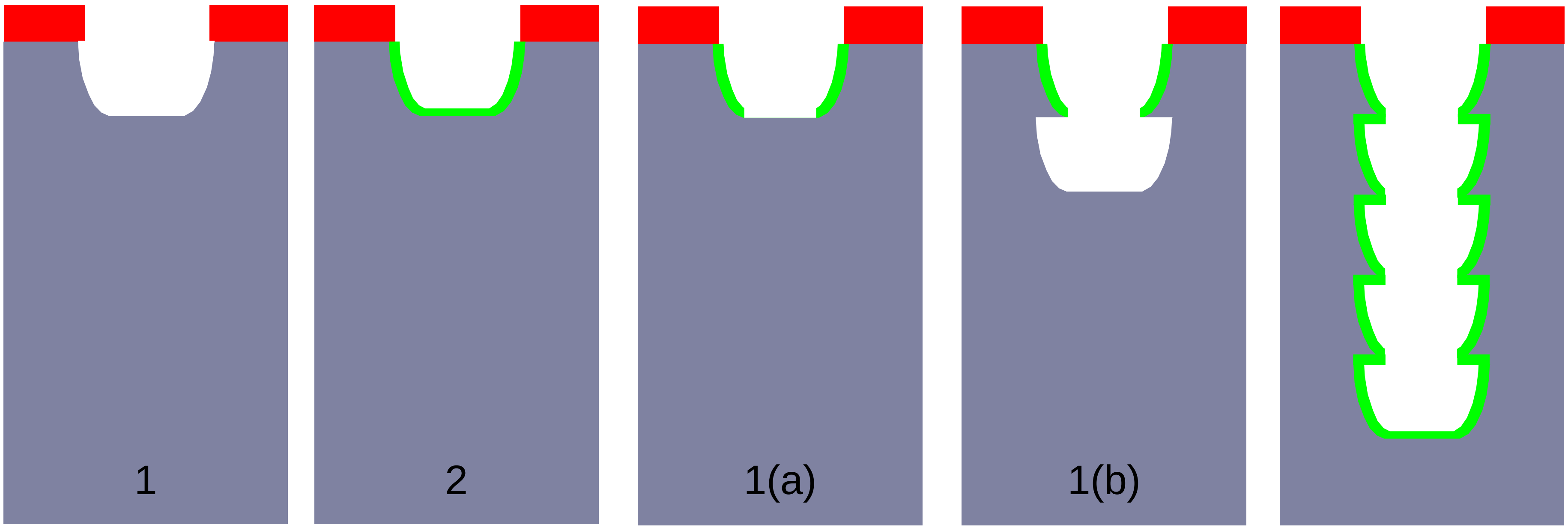


Deep Reactive Ion Etching (DRIE)

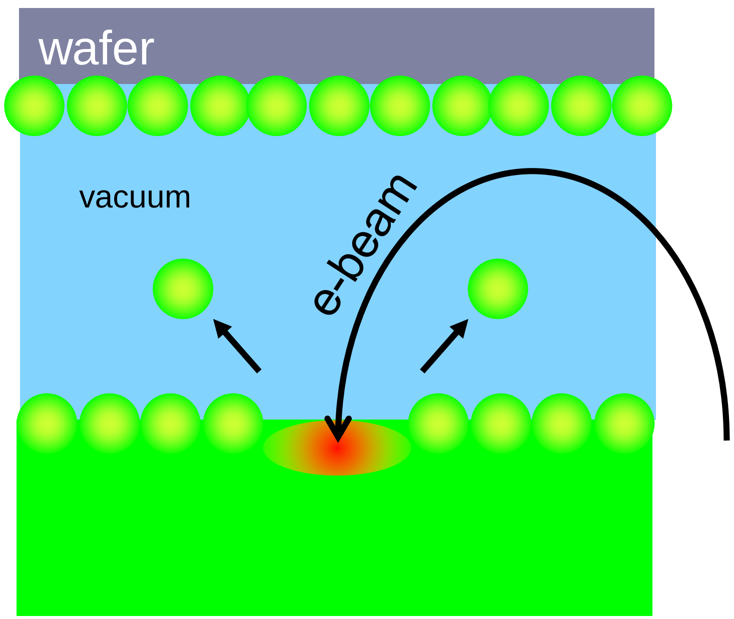
A.k.a. Bosch process (developed at Bosch company)
Two phases are alternatively repeated (each lasting several seconds) to achieve nearly vertical structures with very high aspect ratio (> 200:1):

1. Conventional RIE
2. Deposition of a chemically inert passivation layer.

The passivation layer protects the entire substrate from further chemical etching. During the etching phase, the directional ions sputter (a) the passivation layer at the bottom of the trench (but not along the sides) exposing it to the chemical etchant (b).



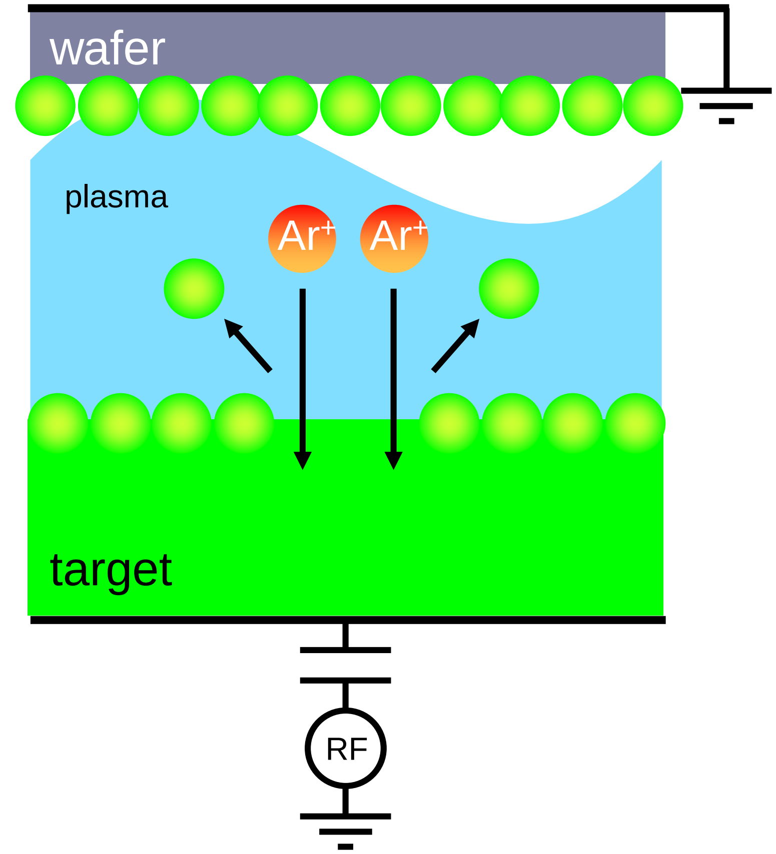
Evaporation



Evaporation of material by:

- Heating (thermal evaporation)
- E-beam bombardment

Sputtering

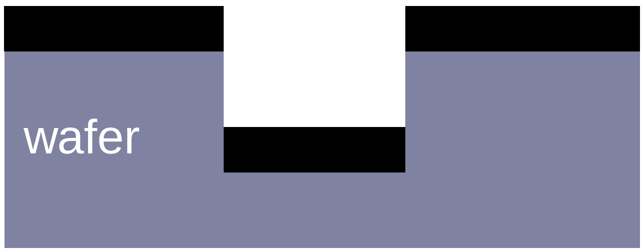


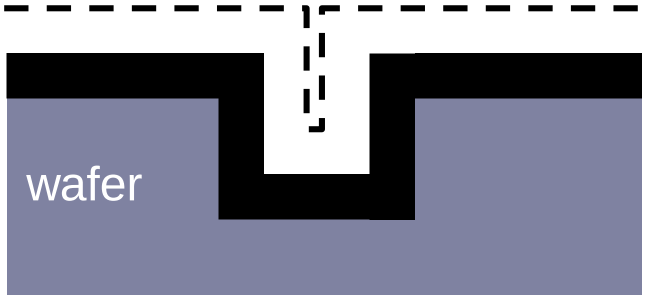
Sputtering of material by bombardment of target with inert ions (Ar^+)

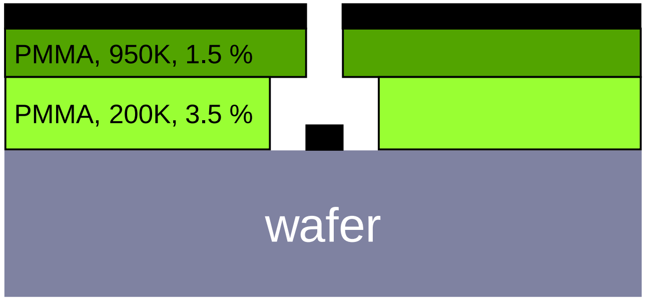
Conformality

Evaporation

Sputtering





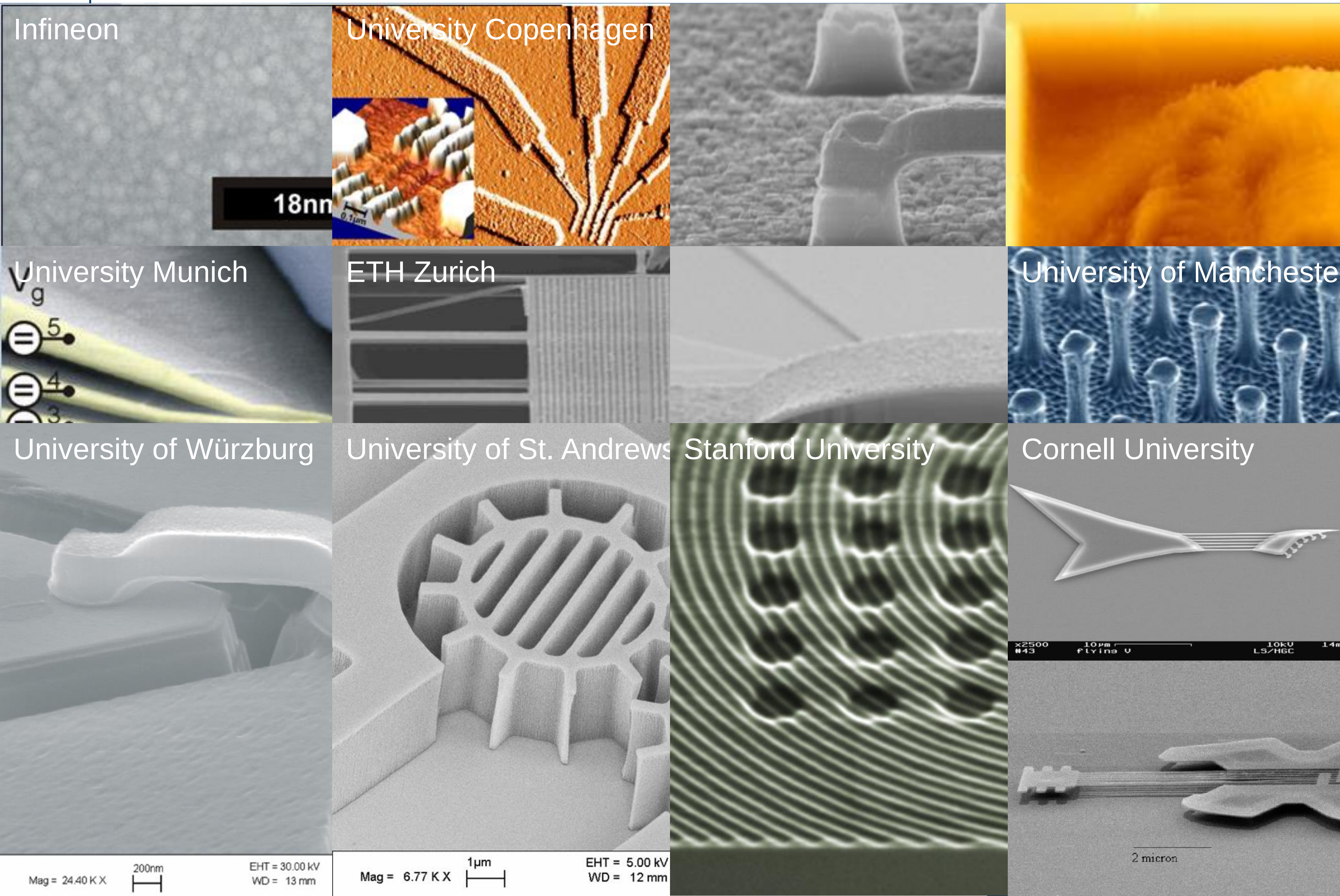


Evaporation
- Used in early Si technology (undercut/lift-off)
- Difficult to deposit well-controlled alloys
- Not suited for large surface coverage
- Requires smooth surface topology

Sputtering
- Used in current Si technology
- Better step coverage
- Less radiation damage
- Wide variety of materials

Step coverage can be advantage or disadvantage, depending on application.

Examples


Infineon
18nm
University Copenhagen
University Munich
ETH Zurich
University of Mancheste
University of Würzburg
Mag = 24.40 K X
200nm
EHT = 30.00 kV
WD = 13 mm
University of St. Andrews
Mag = 6.77 K X
1µm
EHT = 5.00 kV
WD = 12 mm
Stanford University
Cornell University
2 micron