Electron Beam Lithography

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Why use electrons?

Negligible diffraction limitations:

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

With current optical technology, this equates to about 45nm resolution.

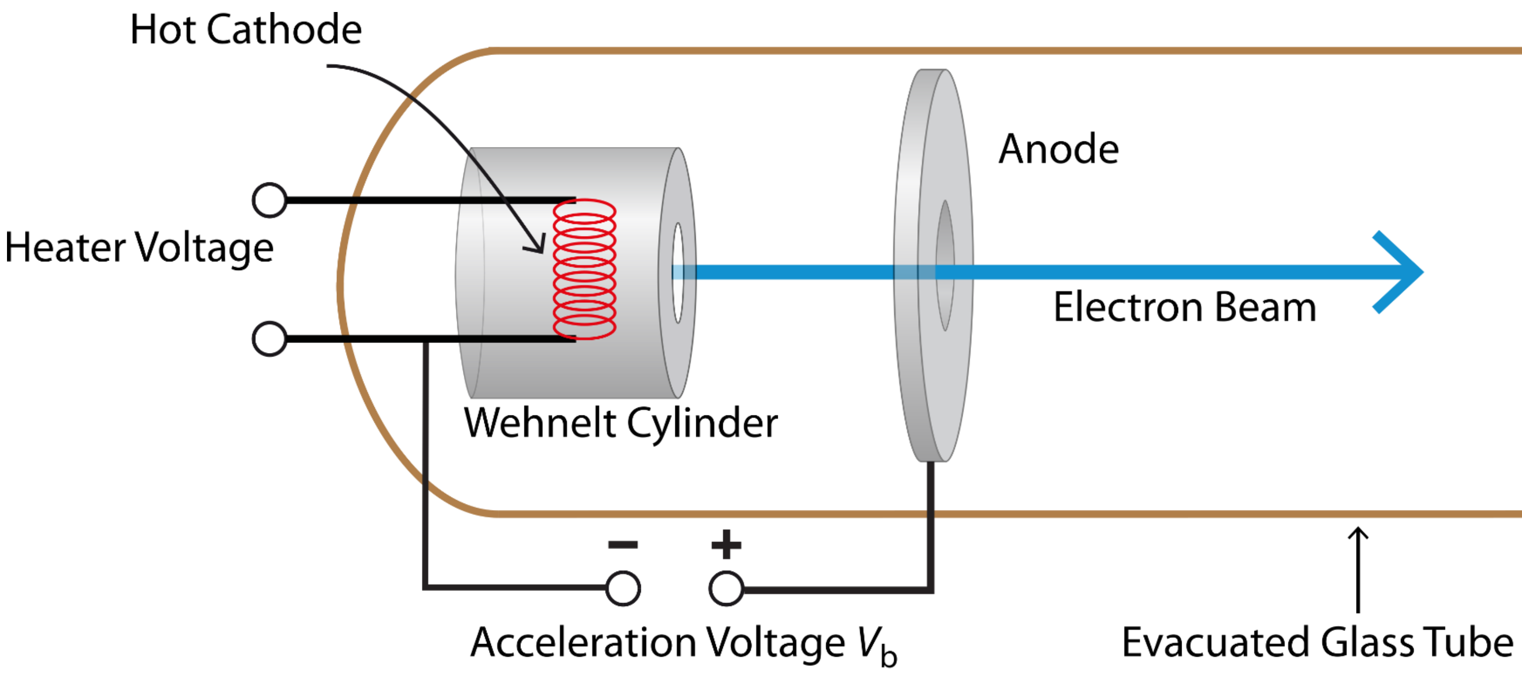
For an electron, wavelength is calculated from its momentum:

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2 * m_e * e * V_a}}$$

An accelerating voltage of 1V has **λ = 1.2 nm**, and 1000V has **λ = 0.03 nm**.

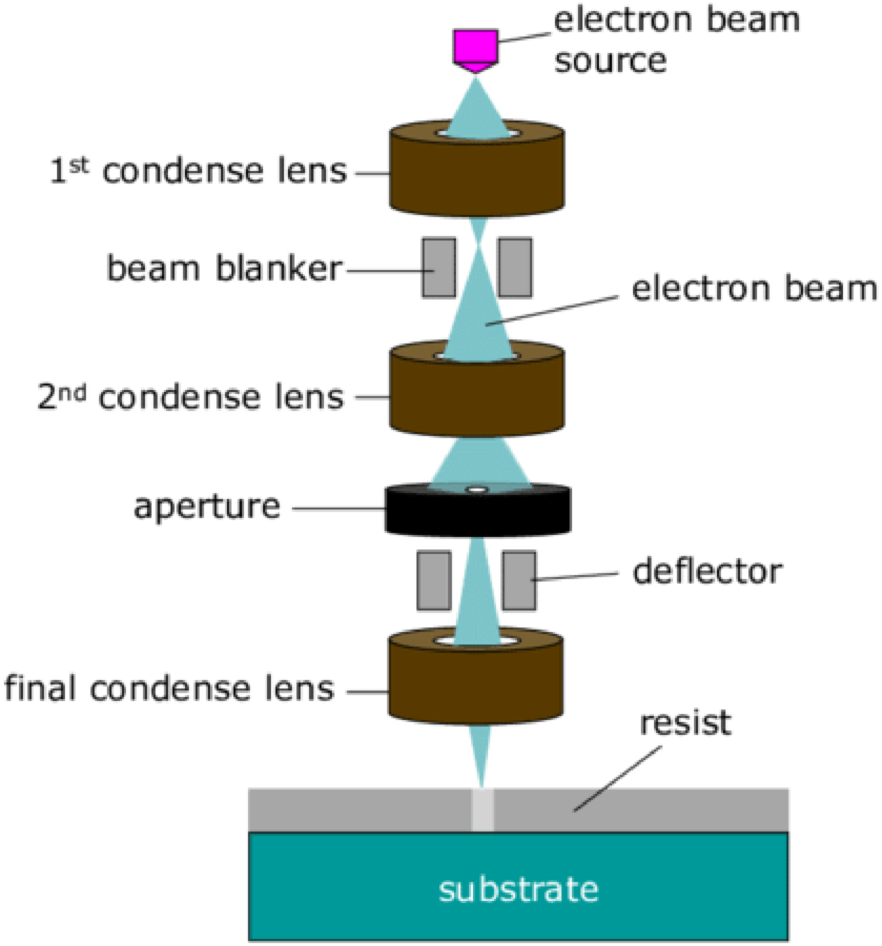
Generating an electron beam:

Electrode gun:

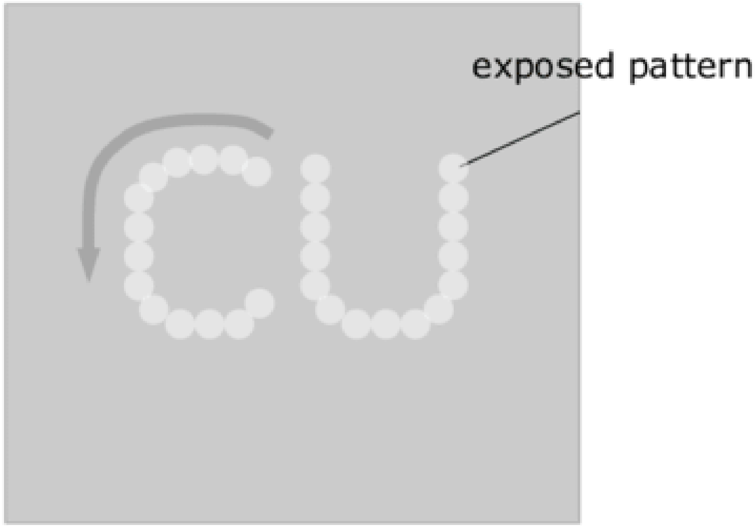


http://www.didaktik.physik.uni-muenchen.de/elektronenbahnen/en/kanone/klassisch/Aufbau.php

Guiding electrons to the resist:



Can use magnetic or electric fields for lenses

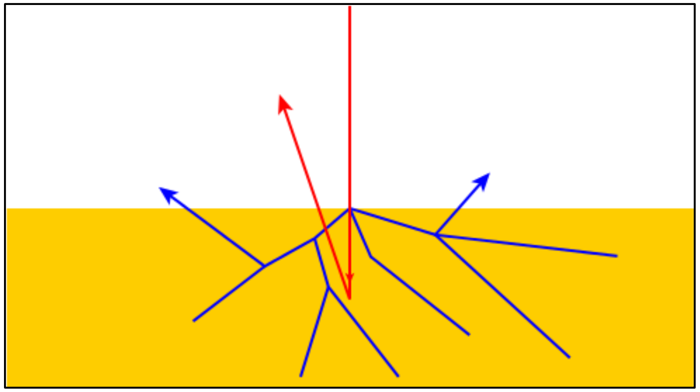


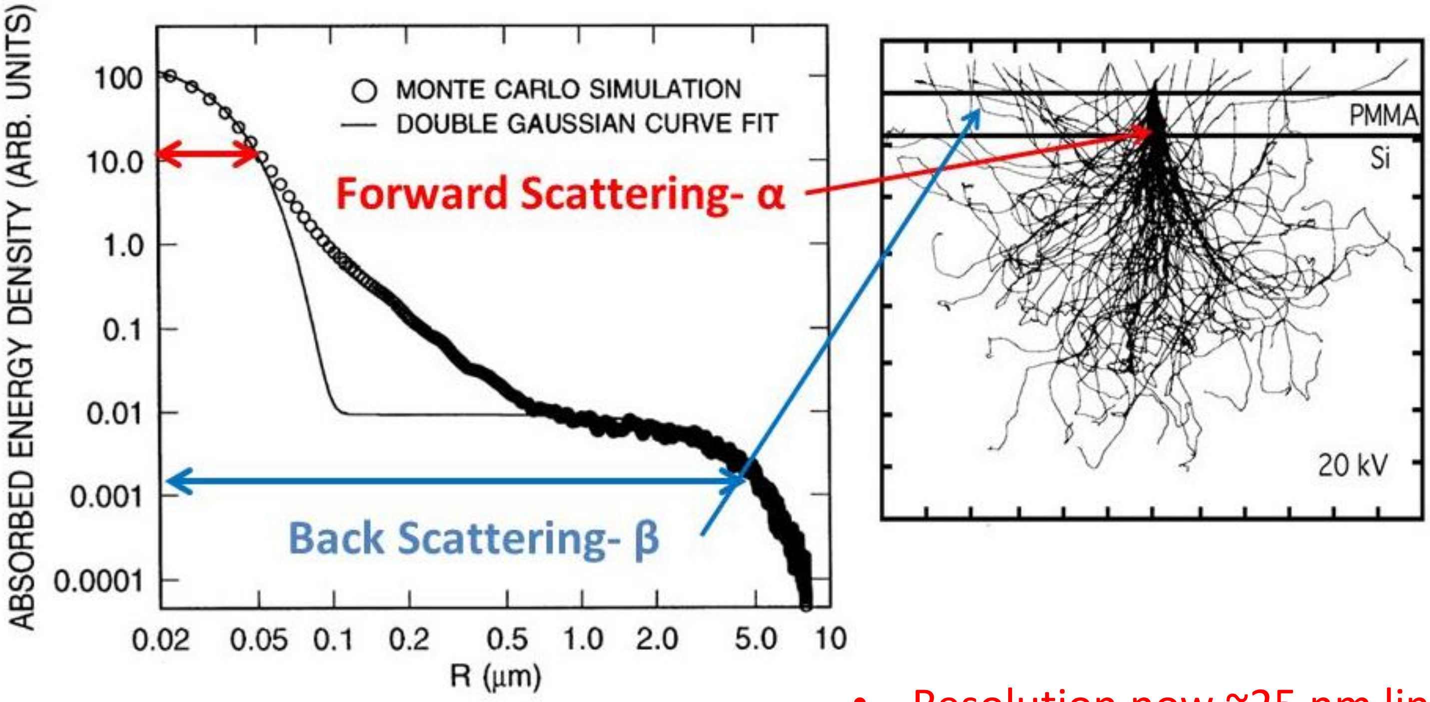
Pimpin, Alongkorn & Srituravanich, Werayut. (2012). Review on Micro- and Nanolithography Techniques and Their Applications. Engineering Journal. 16. 37-56. 10.4186/ej.2012.16.1.37.

Are electrons the answer? Not yet…

Resolution limits from electron scattering:

- Forward scattering (in resist)
- Backscattering (from substrate)



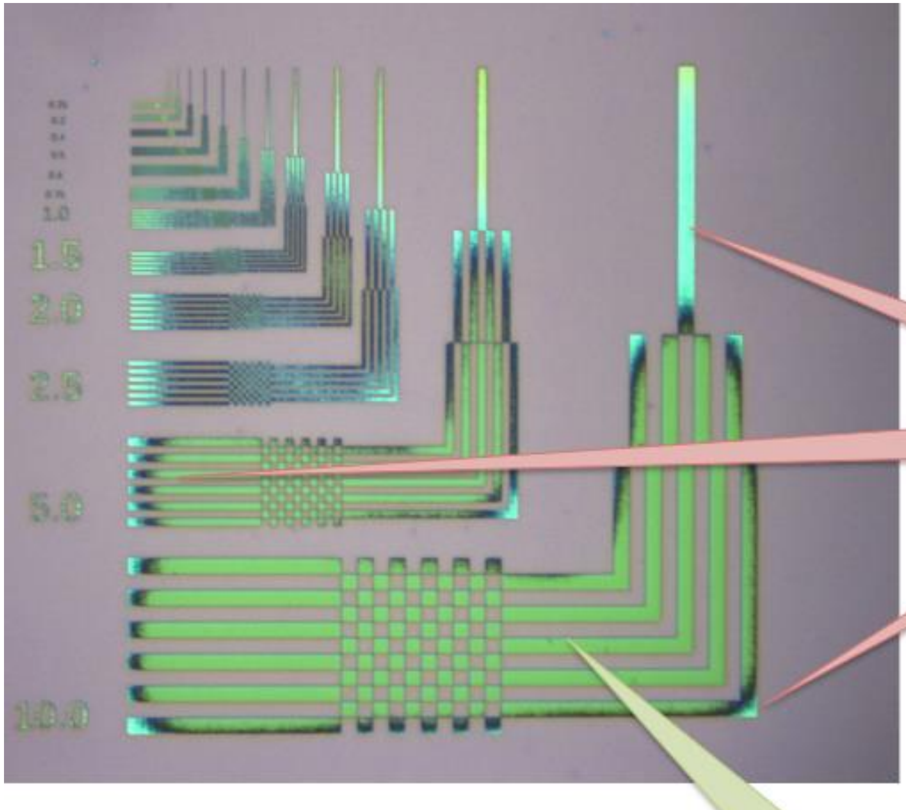


- Resolution now ~25 nm lines and spaces

https://slideplayer.com/slide/6000514/

Proximity Effects

The proximity of closely packed shapes affects the amount of exposure each one sees.

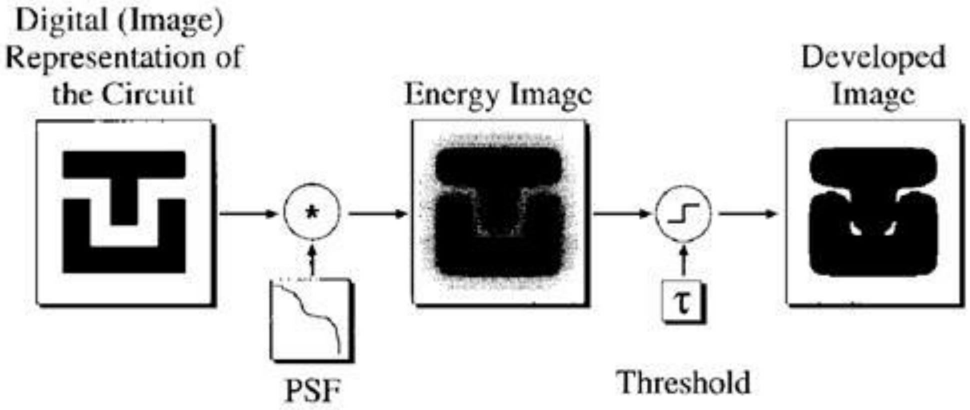


When the densely packed areas are properly exposed, the edges and thin lines are under-exposed.

Varying the electron dose at each location helps alleviate this problem, but makes the process much more complicated.

Proximity Correction

Adjusting the electron exposure based on the pattern location can reduce proximity effects.



The Point Spread Function (PSF) determines the Gaussian shape of the actual resist exposure given the electron beam's point-like areal coverage.

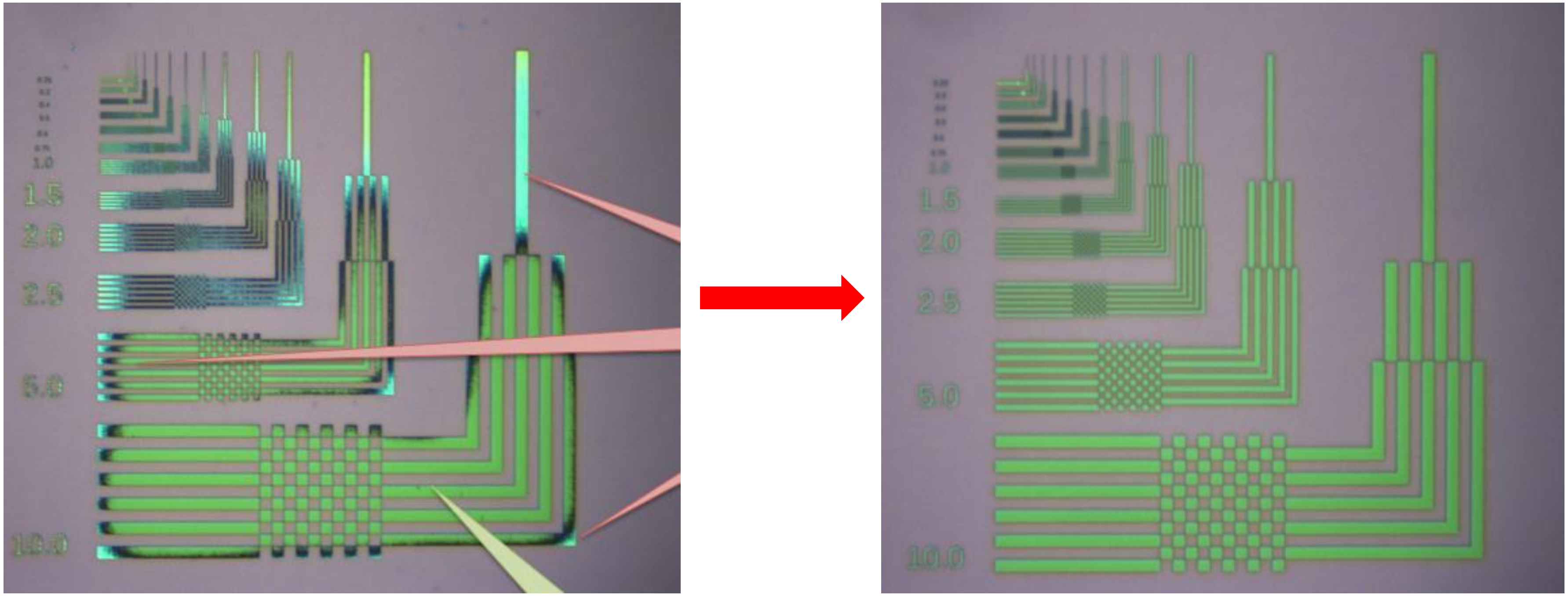
For electron beams, proximity correction can be done in two ways:

- Adjusting the electron dose at locations that require more/less electrons for proper exposure.
- Adjusting pattern dimensions using methods similar to Optical Proximity Correction methods (write a shape that is different than target shape).

Proximity Correction

Adjusting the electron exposure based on the pattern location can reduce proximity effects.

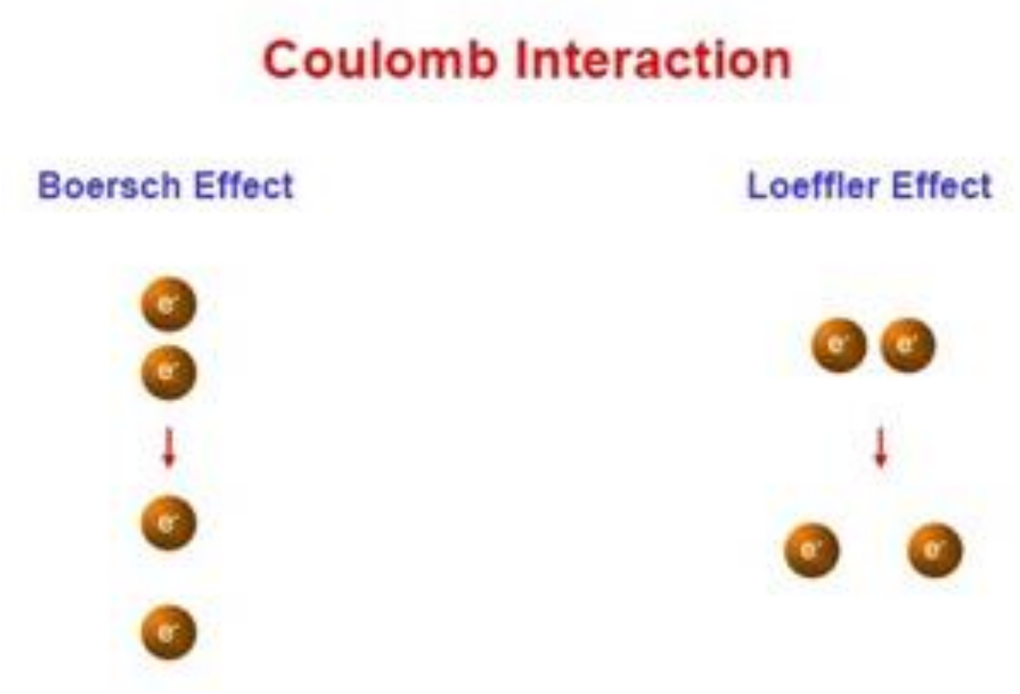
Vary dose at edges and thin lines



https://ebeam.mff.uw.edu/ebeamweb/doc/patternprep/patternprep/proximity_main.html

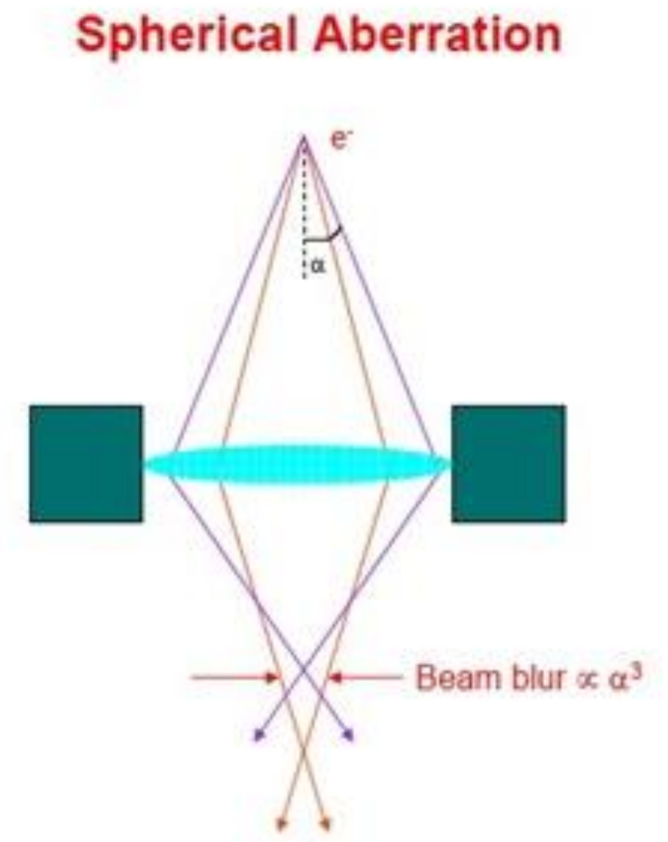
Space charge effects blur the beam.

Space charge effects speed up electrons in their travel direction and spread them apart, resulting in blur.



Chromatic aberration

Chromatic and spherical aberration



Current single beam writing speed is not enough

The minimum time to expose a given area for a given dose:

$$D * A = T * I$$

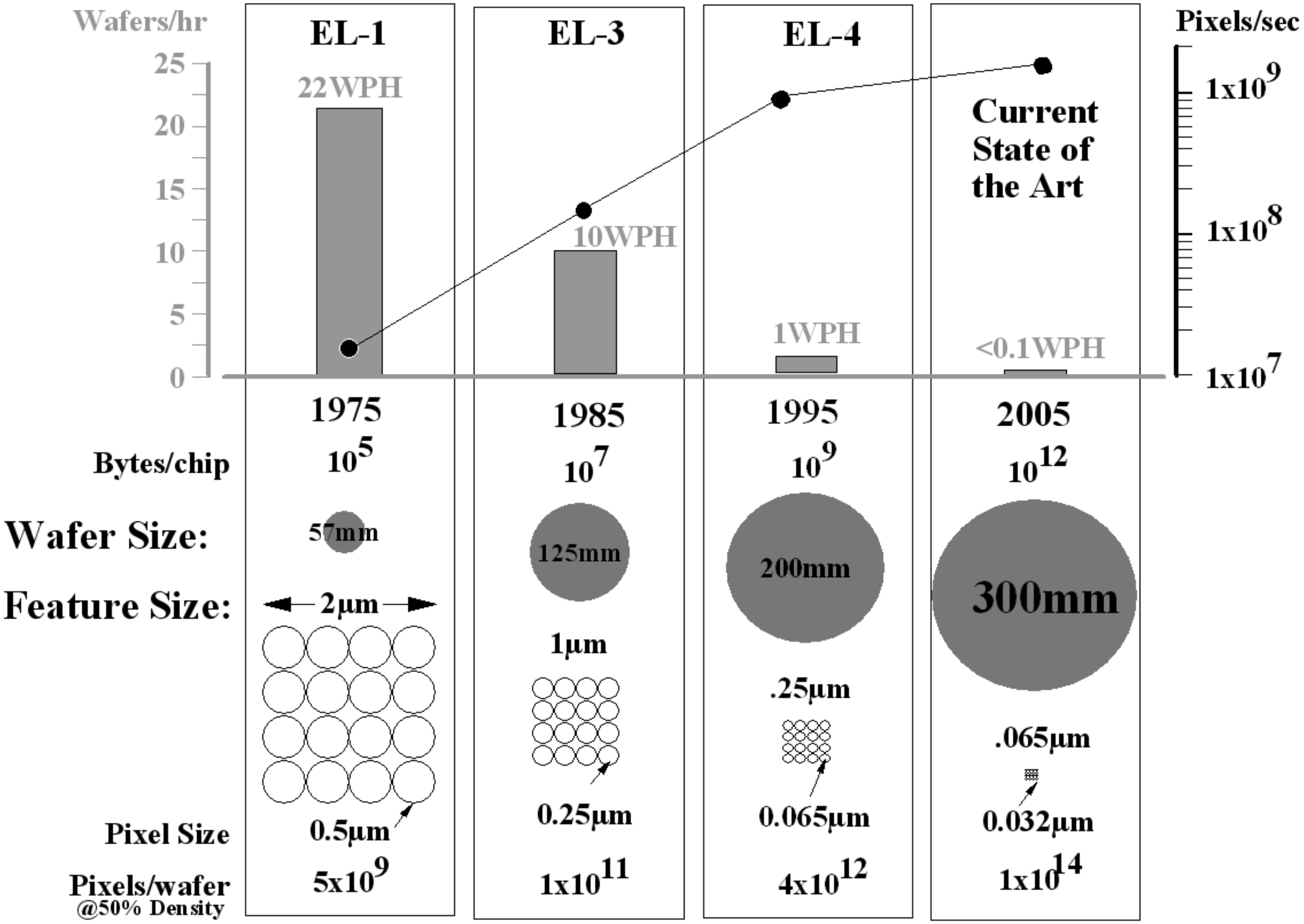
Where:
- D = dose at resist
- A = exposed area
- T = exposure time
- I = beam current

Example:

For 1 cm^2 area, 10^-3 C/cm^2 dose, and 10 nA current, writing time is 10^6 seconds. For a 300mm wafer (700 cm^2), write time, not including stage movement and beam blanking time, would be > 22 years.

Not enough electrons

The biggest issue with bringing Electron Beam Lithography to large scale wafer production is the slow speeds.



MEBES IV – Bell Labs

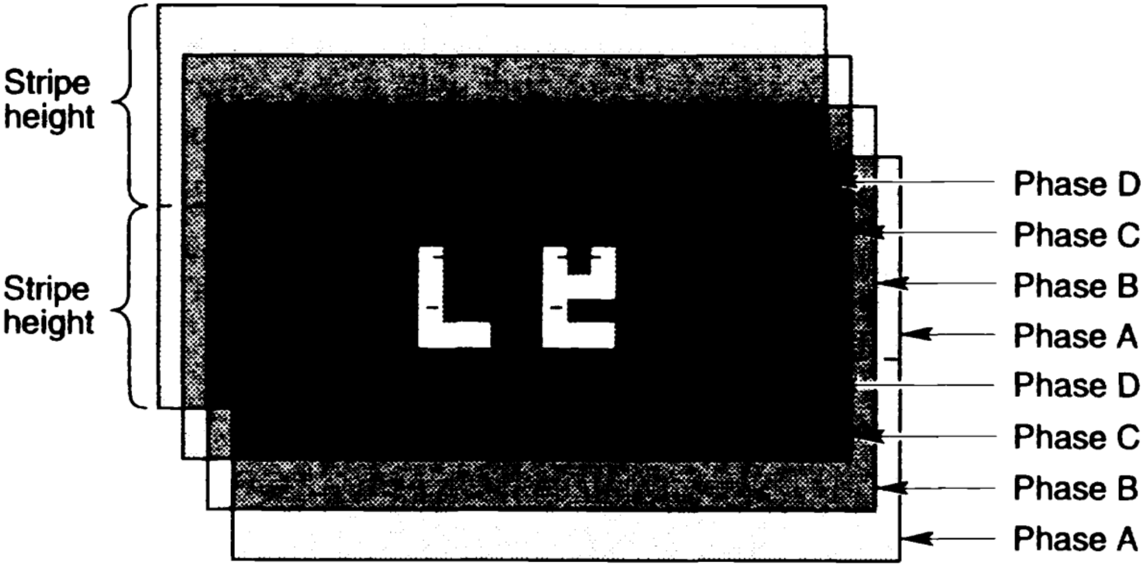
Developed in the 90’s to meet maskmaking requirements of the time.

Specs:

- Write 1X and 5X reticles
- target device was 64-Mbit DRAM
- 125 x 125 mm writing area
- Spot size: 80-400 nm
- Position accuracy: 80 nm
- Feature size: 250 nm

MEBES employed raster scanning writing:

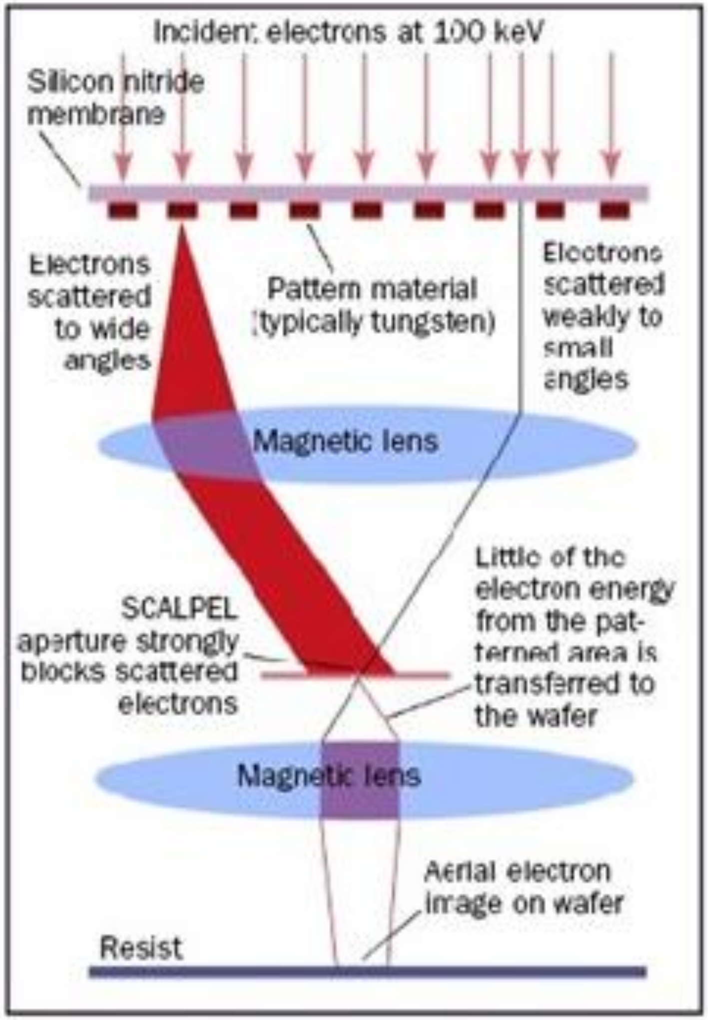
- Chip is divided into stripes
- The stage moves in the x-direction while the beam scans in the y-direction
- Used 4-pass writing strategy.



SCALPEL - Bell Labs

Employed scattering contrast to get images to the wafer:

- Mask is low atomic number membrane patterned with high atomic number material.
- Most electrons (high energy) pass through the mask.
- Contrast is generated from the difference in scattering characteristics in the two mask materials.
- Highly scattered electrons are blocked by an aperture.



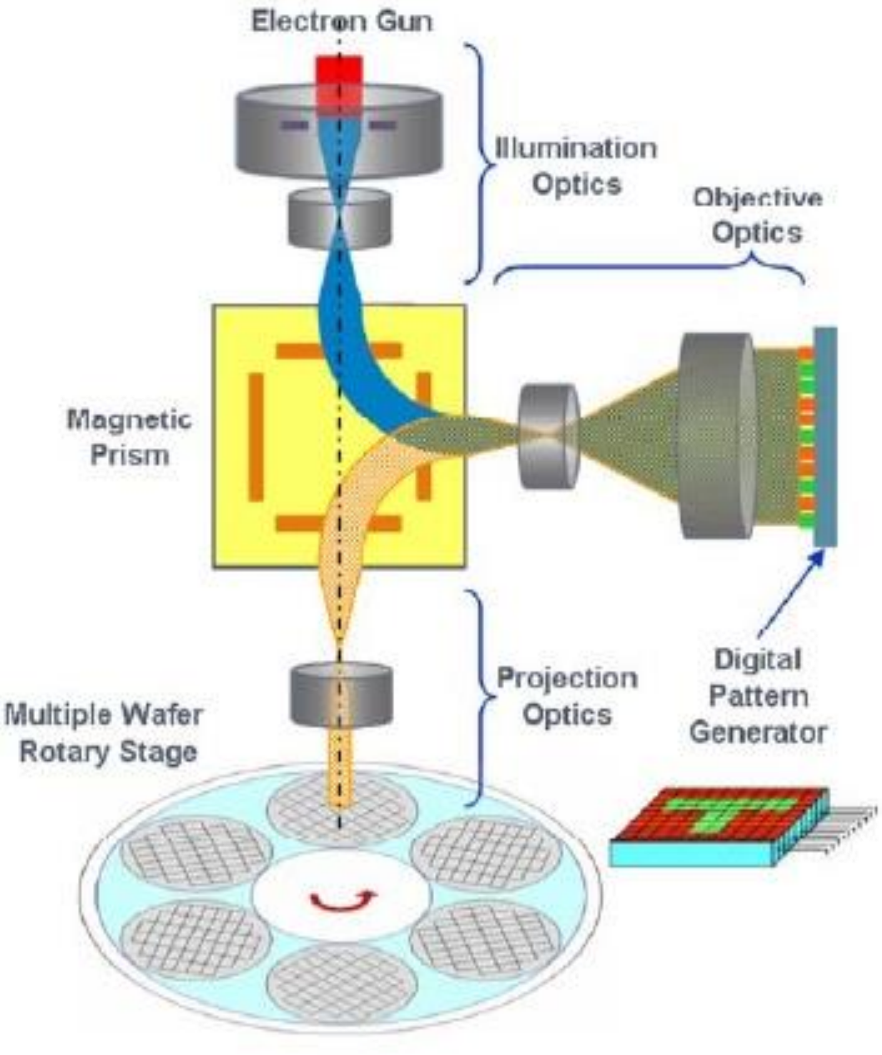
Specs:

- 100 keV electrons
- Very little of the total energy reaches the resist.
- 4:1 demagnification of the mask.
- 70 nm feature sizes possible.
- Step and scan method for both the wafer and mask.
- ~45 wafers/hour throughput (200mm).

REBL - KLA-Tencor

Employed reflective electron optics with a Digital Pattern Generator (DPG):

- DPG controls ~1 million parallel beams.
- Uses reflection instead of transmission.
- Rotary stage allows for multiple wafer processing.
- Grey-tone exposure to supply non-binary doses to resist.



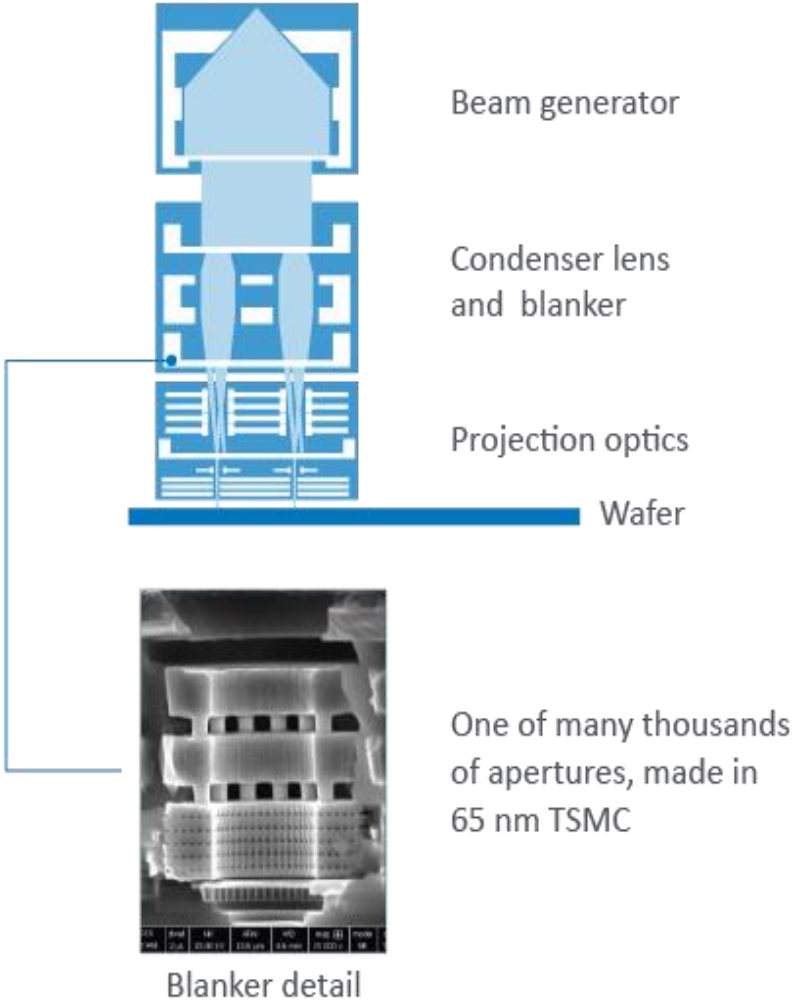
Specs:

- 50X demagnification.
- 60 nm feature sizes possible.
- Electron optics are static system.
- 20 Tbps data transfer to DPG required.
- ~10 wafers/hour throughput.

Mapper – MAPPER Lithography

Wide electron beam is split into thousands of smaller beams:

- MEMS deflectors turn beamlet deflection on and off.
- Deflected beamlets are blocked and non-deflected beamlets pass through.
- Micro lens array demagnifies non-deflected beamlets to 25 nm Gaussian spot.
- Wafers are scanned while beams are static.



Specs:

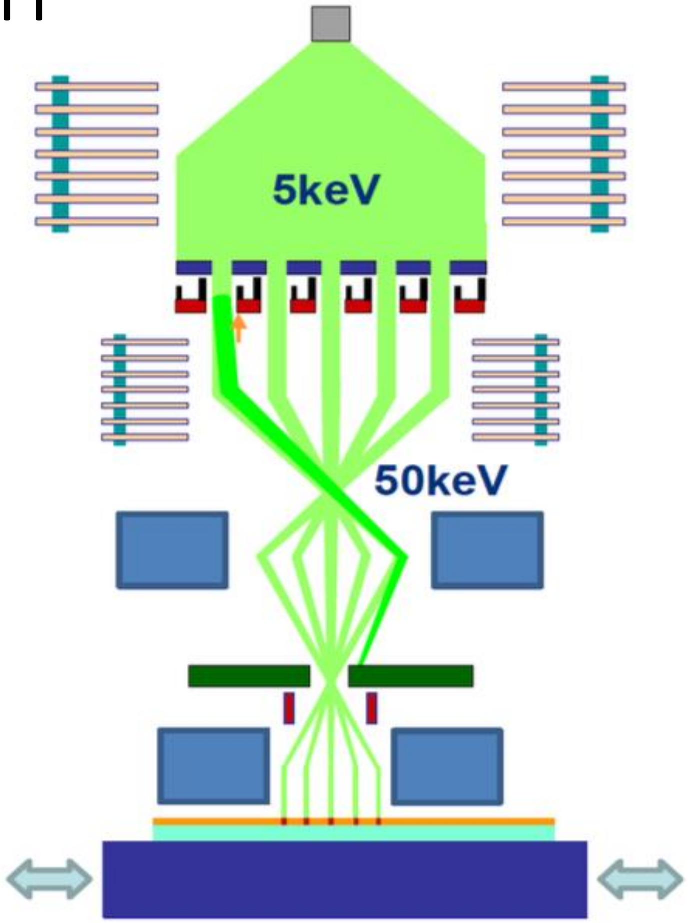
- 5 keV electrons.
- 3 cm beam diameter.
- 65,000 individual beamlets.
- 45 nm feature sizes possible.
- Electron optics are static system.
- ~10-20 wafers/hour throughput (~40 estimated with new 650,000 beamlet upgrade).

https://mapper.nl/technology/

IMS – IMS Nanofabrication

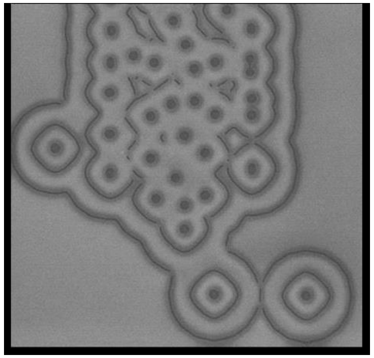
High-throughput multi-beam mask writing:

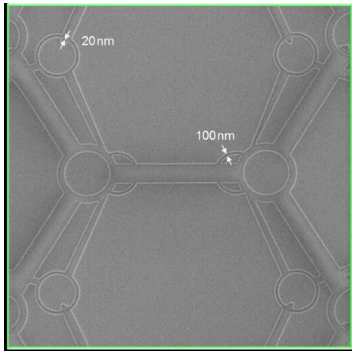
- Employs programmable aperature plate system.
- Demagnification of beams with magnetic lenses to 20 nm beam spot size
- Wafers are scanned while beams are static.
- Throughput is independent of pattern complexity.



Specs:

- 5 keV electrons.
- 200x demagnification.
- 262,000 individual beamlets.
- 30 nm feature sizes possible.
- Electron optics are static system.
- <10 hr mask writing time (current masks can take 30+ hrs to write).





https://www.ims.co.at/wp-content/uploads/2016-10-17_BACUS-2016_IMS_MBMW-101_998505.pdf

Conclusion

- Electrons beat the diffraction limit associated with optical lithography.
- Electrons can be guided and focused, similarly to photons, by using magnetic or electrostatic lenses.
- Electron scattering is the main limitation of writing small features.
- Proximity correction can help limit scattering effects, but can not get anywhere near the de Broglie limit of electrons.
- Electron throughput severely limits using E-beam technology for large scale production.
- Large area beams and multi-beam systems are the current approach to solving the throughput problem.