PC3242 Part II

Topic	Text Book (Zhen Cui '05)	Lectures
Optical lithography	Chapter 2	1, 2 & 3
Electron Beam Lithography	Chapter 3	4 & 5
Focused Ion Beam Technology	Chapter 4	
Low Energetic Ions (keV)		5, 6, 7 & 8
SIMS	Extra material provided	
FIB in Lithography	Chapter 4	
High Energetic Ions (MeV)	Extra material provided	8
RBS	Extra material provided	9
Light ions in lithography	Extra material provided	10
Etching	Chapter 7	10, 11
Nano Imprint Lithography	Chapter 6	12
3DP Three Dimensional Printing	Extra material provided	13

JA van Kan 2024

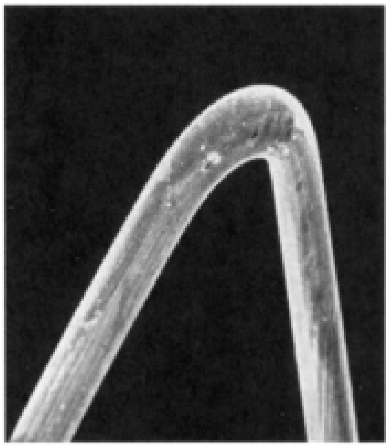
E-Beam

Which gun would you want to use for Electron beam writing?

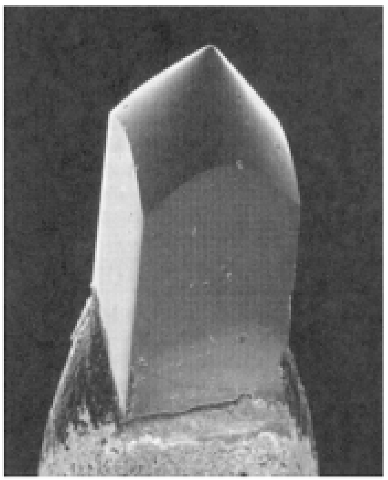
Electron guns

Electron guns extract electrons from filament and focus electrons into beam

Cathodes



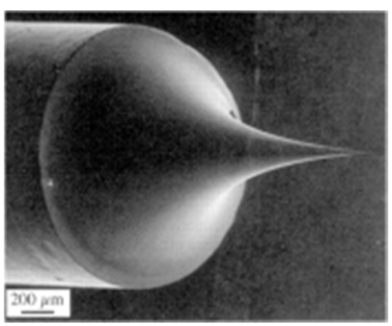
W wire filament



LaB6 crystal filament

Thermionic electron gun

Commonly used
Operate at high temperatures
Pressure10^{-7}-10^{-8} Torr



W field emission source

Field emission gun (FEG)
Cold or thermal

Pressure< 5×10^{-10} up to 10^{-12} Torr otherwise the surface gets contaminated which affects the stability

E-Beam

Electron guns

➔Cold **field emission** guns are not (yet) stable enough for e-beam writing

➔The thermal field emission guns are **most preferred** since they have

- **high brightness**
- **low energy spread**
- **long live-time**
  - If you don't need ultimate focusing performance, a thermionic electron gun might be better as you don't need extremely low pressures!

Numbers in microscope

Typical beam currents in a microscope are 1nA to 1μA
For a current of 1μA this is 6.2×10^{12} electrons/sec
Electrons are separated by ~25μm in column on average

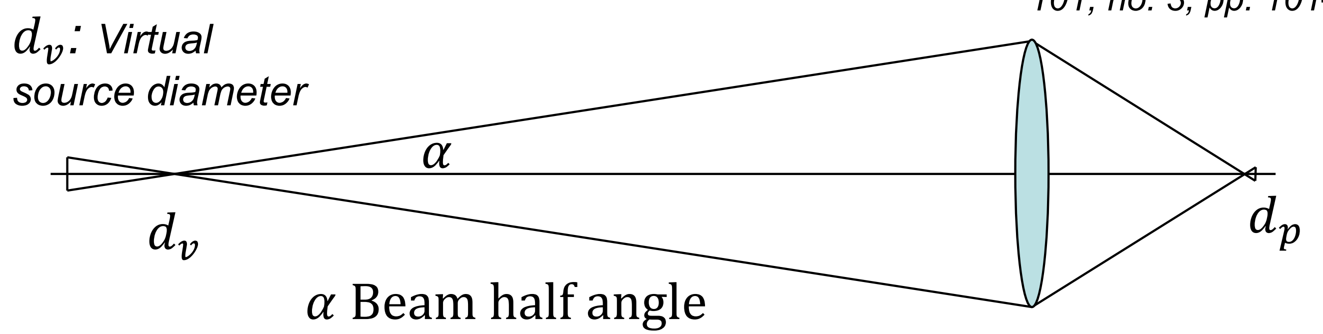
Electrons repel each other ➔ space charge leads to defocusing

E-Beam spot size

$$d_P = \left\{\left[d_I^{1.3} + (d_A^4 + d_C^4)^{1.3/4}\right]^{2/1.3} + d_S^2\right\}^{1/2}$$

Beam size depends on many types of imperfection of the system

J. E. Barth and P. Kruit, "Addition of different contributions to the charged particle probe size," Optik (Stuttg)., vol. 101, no. 3, pp. 101–109, 1996.



$$d_I = \frac{d_v}{Dem}$$

d_I : Demagnified virtual source size

d_v: Virtual source diameter

$$d_S = 0.18 C_S \alpha^3$$

d_s : Spherical aberration

$$d_C = 0.6 C_C \frac{\delta U}{V} \alpha$$

d_c : Chromatic aberration

$$d_A = 0.54 \frac{\lambda}{\alpha}$$

d_A : Diffraction aberration

C_c Chromatic aberration coefficient

C_s Spherical aberration coefficient

δU Beam energy spread

λ is the de Broglie wavelength (See A/P Ho's notes)

V Acceleration voltage

Dem lens demagnification

Note I use slightly different constants as in A/P Ho's notes & I added d_A

E-Beam

Ultimate resolution

Fabrication below 100 nm is easy

Not easy to fabricate below 20-30 nm

Resolution limiting factors

<u>Beam spot size</u>

- Aberrations of electron optical elements mainly:
  1) Spherical
  2) Chromatic
  3) Astigmatic

Spherical aberrations ➔ (beam spread angle)^3

- Solution smaller apertures ➔Less beam current (slower writing)
- **Field emission** sources are very useful here!

  They have low energy spread and therefore less **chromatic aberrations** as well.

Modern systems can achieve a few nm spot sizes

Next generation is aiming at 1 nm

E-Beam

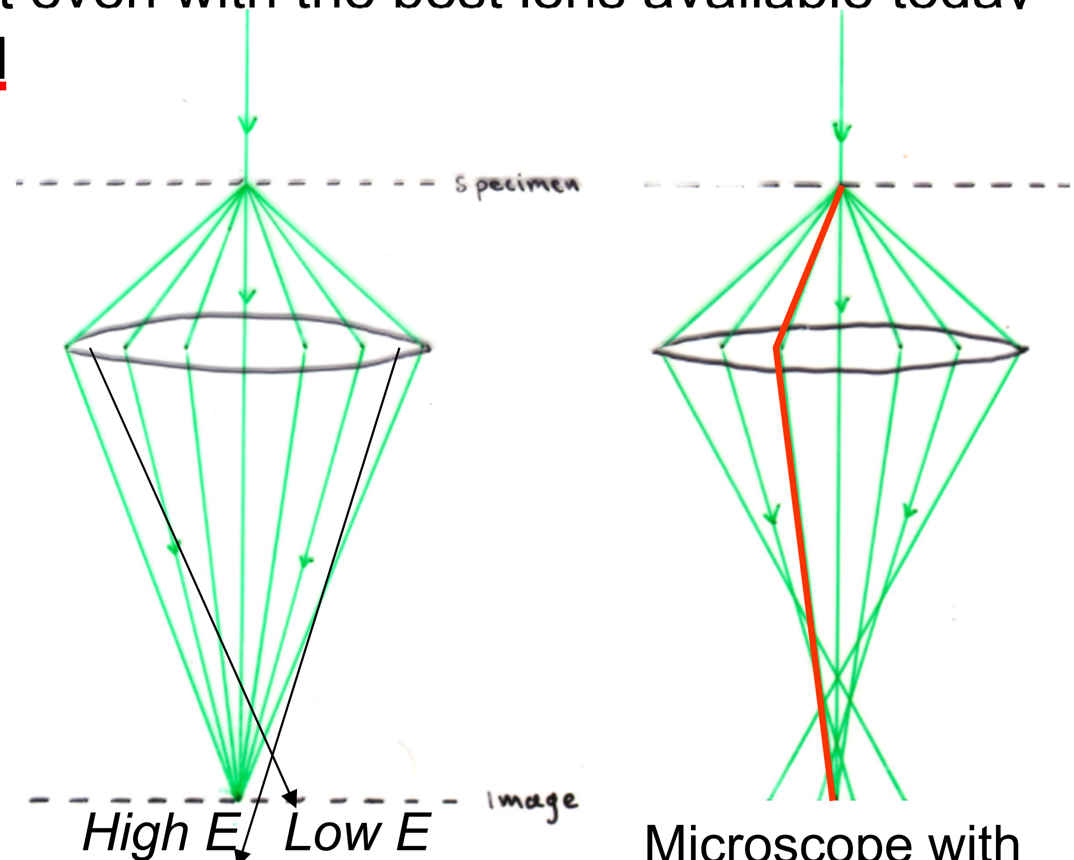
Electron lenses: aberrations (Recap)

Electrons going through the edge of the lens are bent too much. This gives rise to spherical aberration

The <u>spherical aberration</u> is so bad that even with the best lens available today only electrons focused within **<u>10 mrad</u> (0.6°)** of the optic axis are focused correctly onto the image

A good optical microscope can focus light rays that are within 45° of the optic axis!

Thus the electron beam must be accurately aligned along the centre of all lenses!

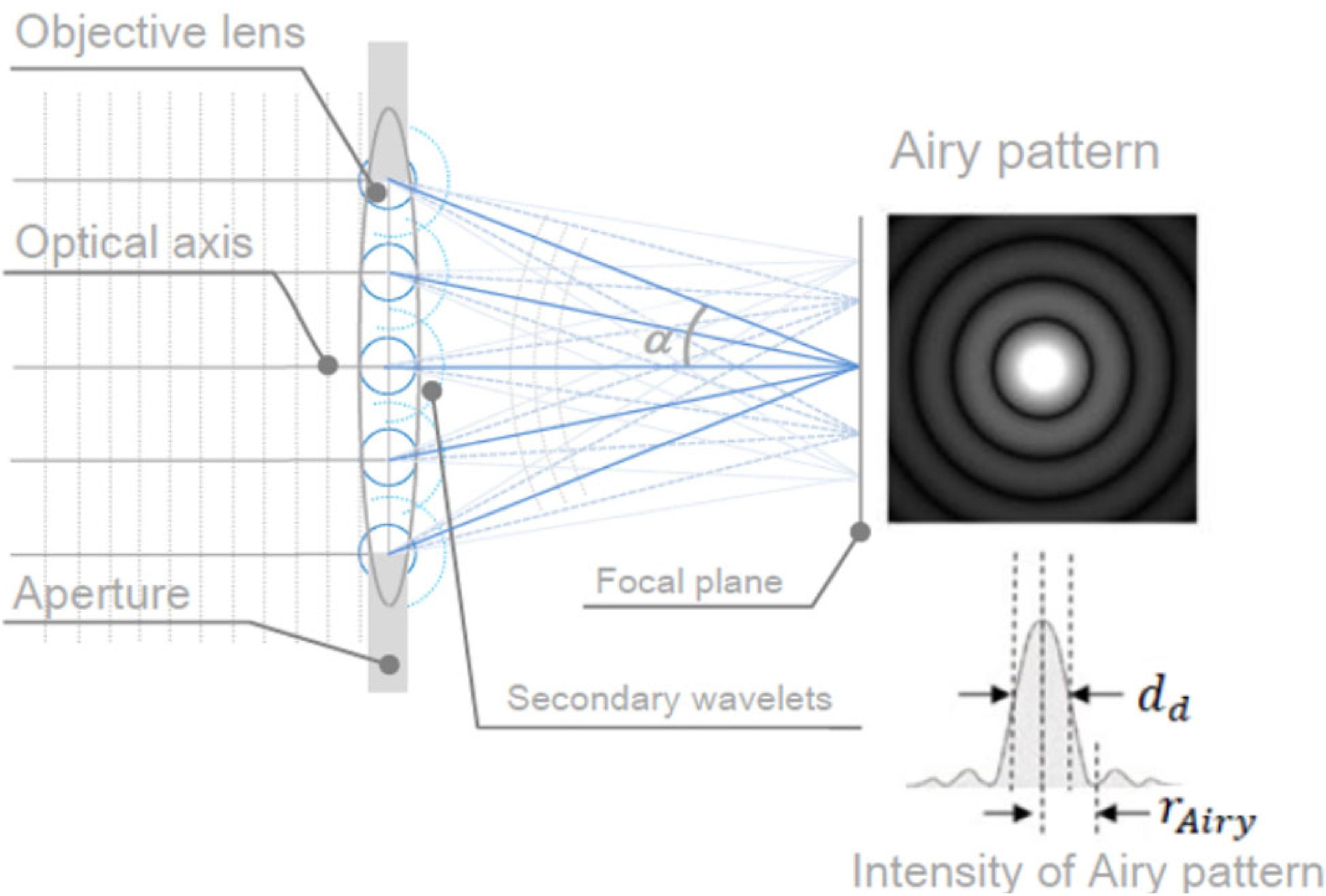


Perfect microscope
No Spherical aberrations

Microscope with
Spherical aberrations

Beam energy variation leads to <u>chromatic aberrations</u> E variation in source.

E-Beam
d_A Diffraction Aberration



E-Beam

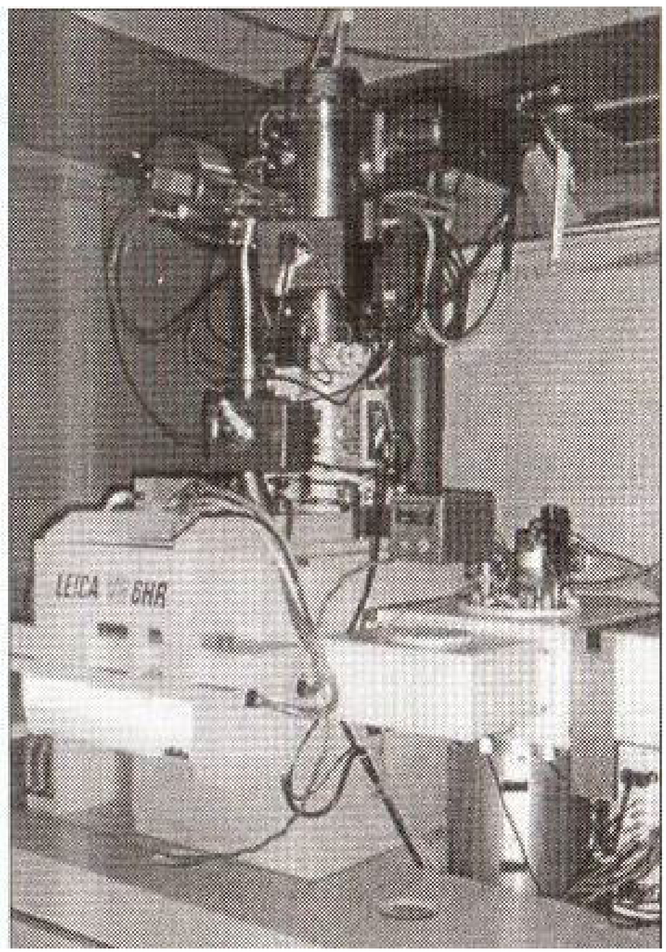
Mean Free Path (MFP)

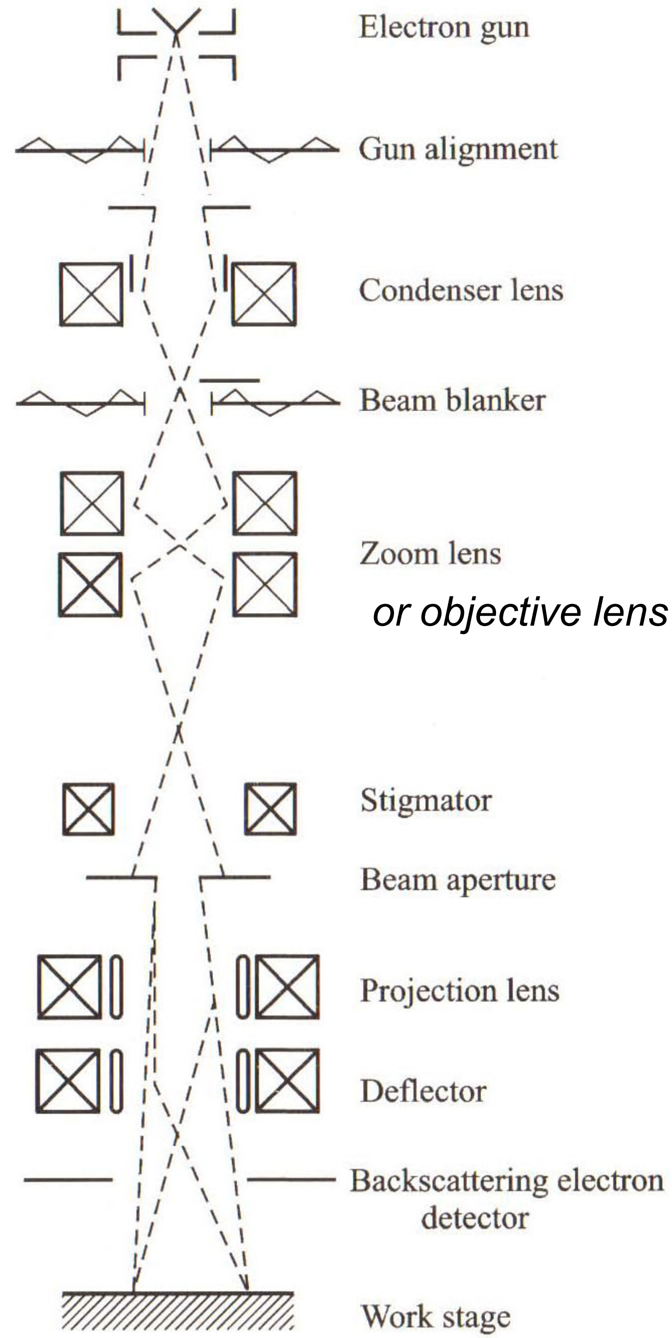
Electrons are scattered by air

$$\text{MFP} \approx \frac{5 \times 10^{-3}}{\text{P (Torr)}} \text{(cm)}$$

To prevent scattering:
Vacuum $<1\times10^{-4}$ Torr
(mfp ~ 50 cm)

In practice vacuum ~ 1×10^{-5} to 1×10^{-10} Torr





Schematic view inside

E-Beam

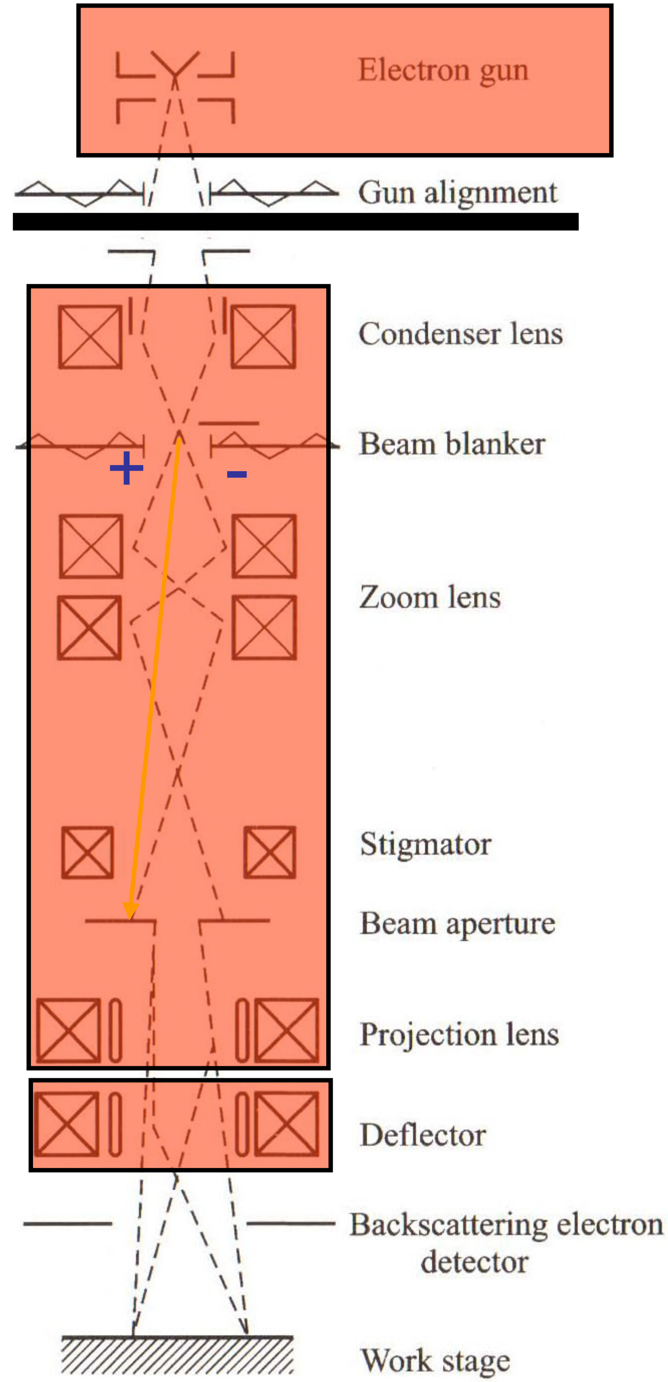
Electron beam lithography systems

Basic components in an electron optical system are shown in red.

- Electron Gun
  Note it operates at high voltage 10-100 keV and sits at negative potential ➔ special requirements for pumps.

- Gun alignment + apertures are crucial!
  ➔ Spherical aberrations!

- Beam blanking; a fast electrostatic deflector which deflects the beam from the optical axis.



Schematic view inside

Beam Scanning

•**magnetic deflector** slow: less aberration & distortion used for large deflection.

• **electrostatic deflector** fast; used for small field scanning.

E-Beam

Electron beam lithography systems

Faraday cup

• Used to measure beam current ➔ Reproducible structure writing

Backscatter detector

• Typically used to inspect the samples, mapping of alignment markers

Exposure methods

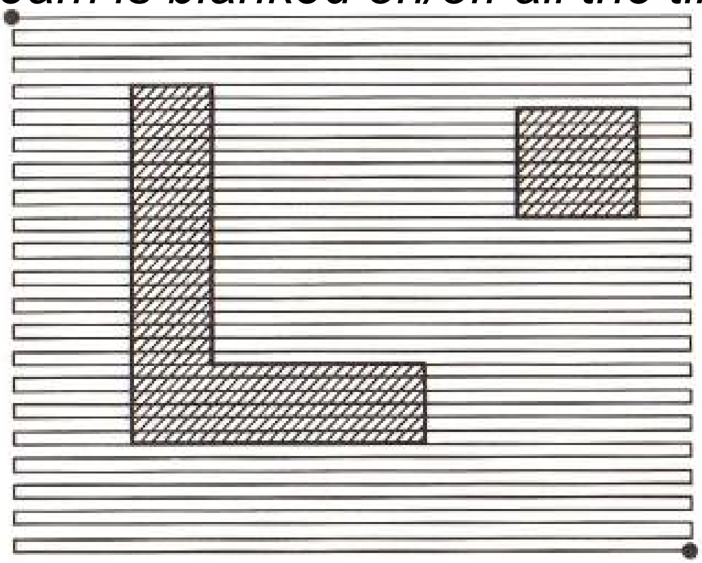
Direct beam write systems:

1. Raster scanning systems
2. Vector scanning systems
3. Shaped beam systems

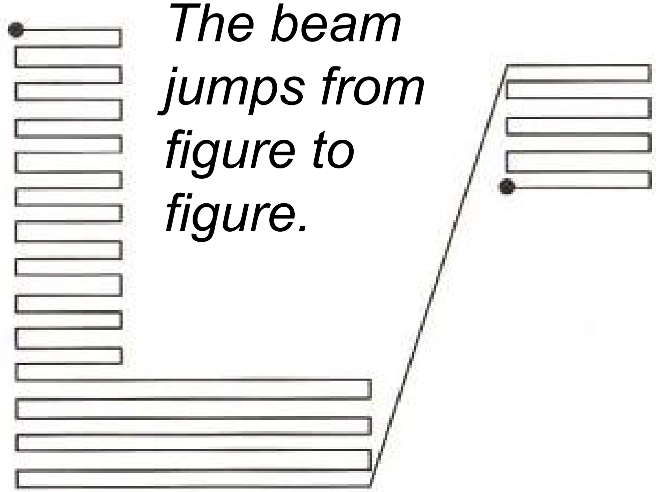
E-Beam

Modes of direct write operation

Beam is blanked on/off all the time



1 Raster Scan



2 Vector Scan

Fig.3.9. Comparison of raster scan (a) and vector scan (b)

3 Shaped Beam System

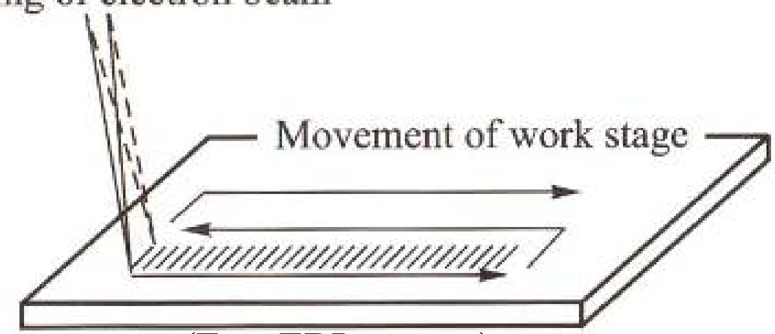
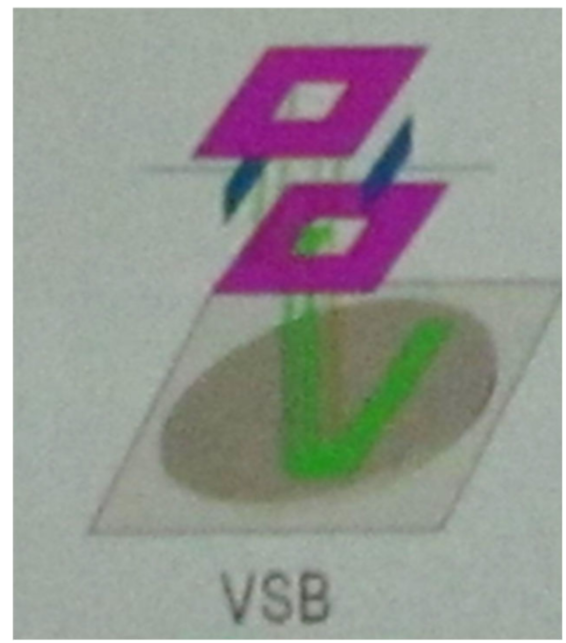


Fig.3.10. Combination of raster scan and work stage movement in MEBS system



Variable Shaped Beams
(Raith system)

E-Beam
Electron beam lithography systems

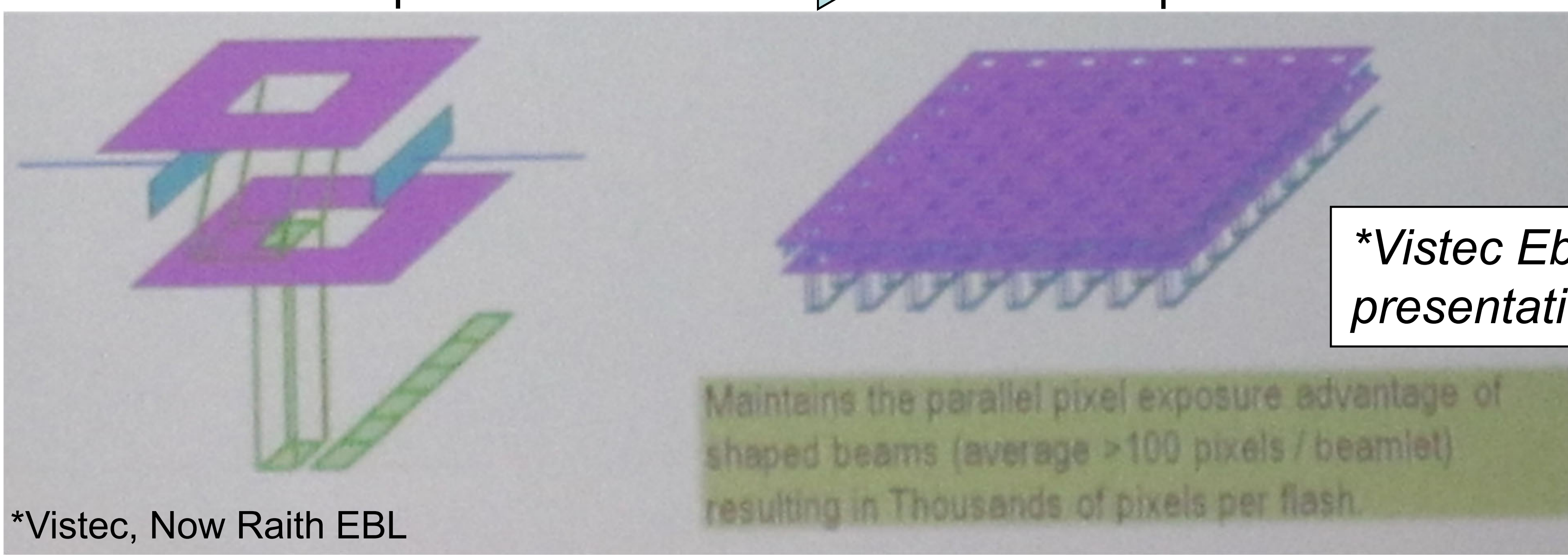
<u>Important points to consider before buying an e-beam lithography system</u>

<u>Minimum spot size</u> ← → <u>System resolution</u> ← → <u>Throughput</u>

<u>Accelerator voltage</u> = e-beam energy.

- The resolution depends on the beam energy, higher beam energy results in less beam spread → higher resolution
  But you need more electrons!
- You can use thicker resist when using higher energies.

Variable Shaped Beam → Multi Shaped Beam



*Vistec, Now Raith EBL

*Vistec Ebeam system presentation at MNE 2011

E-Beam

Electron beam lithography systems

Beam current is directly linked to the speed of lithography and beam size.

Limited by the speed of the scanning system

Vector system < 50 MHz

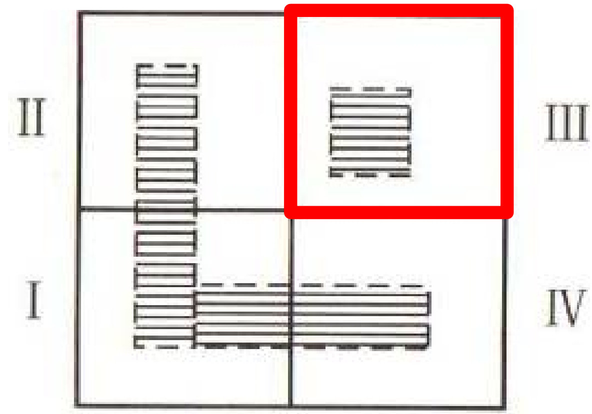
Raster system < 500 MHz

High current densities leads to **coulomb repulsion** (space charge)

If small **Scan Fields** can be used stitching errors can be avoided.

Stitching errors / Overlay accuracy depend on the **stage quality** & the (thermal) stability of the system.

Large area exposures need stitching of fields; typical error is 30-60 nm in overlay. You need to keep this in mind when you design your patterns. It can be less if you have a dedicated interferometer stage.



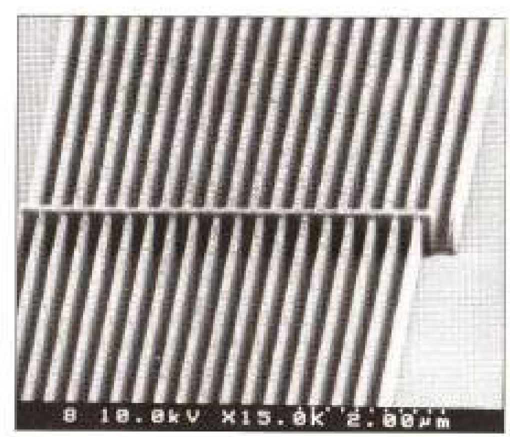
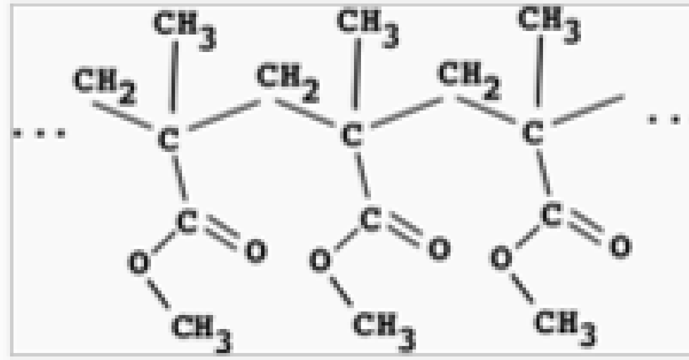


Fig.3.19. Disruption of continuous lines due to field stitching error

E-Beam
Electron beam Resist PMMA

Polymethyl Methacrylate (PMMA) ($C_5O_2H_8$) is the first discovered e-beam resist

1933 the German chemist Otto Röhm patented and registered the brand name *PLEXIGLAS*®.
In 1936 the first commercially viable production of acrylic safety glass began.



Structure of the PMMA polymer

PMMA can be found in many forms:

During World War II acrylic glass was used for submarine periscopes, and windshields, canopies, and gun turrets for airplanes.

Two white motorcycle helmets, full-face and open-face. Use of the color white helps increase visibility.

An electric bass guitar with its body made out of perspex

E-Beam

Electron beam Resists and Processes

E-beam resist are sensitive to the energy deposition due to electrons.

The process of either chain scission or cross linking goes in a similar way as in optical lithography.

In e-beam writing we have also positive and negative resists as well as chemically amplified resists.

Resist can be divided into groups depending on their applications:

Mask patterning **High resolution direct write**

In mask patterning we need to pattern large areas with relaxed requirements on resolution. In 13.4 nm EUV we use reflective optics!
➔ High sensitivity for fast fabrication!

In high resolution resists, structures are fabricated not feasible with optical lithography.

E-Beam

Electron beam Resist: PMMA

If you take a piece of PMMA like these high heel shoes and **dissolve** it in **Anisole** (~10% by weight) you can **spincoat** it on a wafer and get a layer of **several microns** in one coat.

Chlorobenzene was used before but is a health hazard!

PMMA is an extremely powerful e-beam resist, it can achieve features down to 4-5 nm.

Or even ~ 2 nm (2017). Although this is debatable

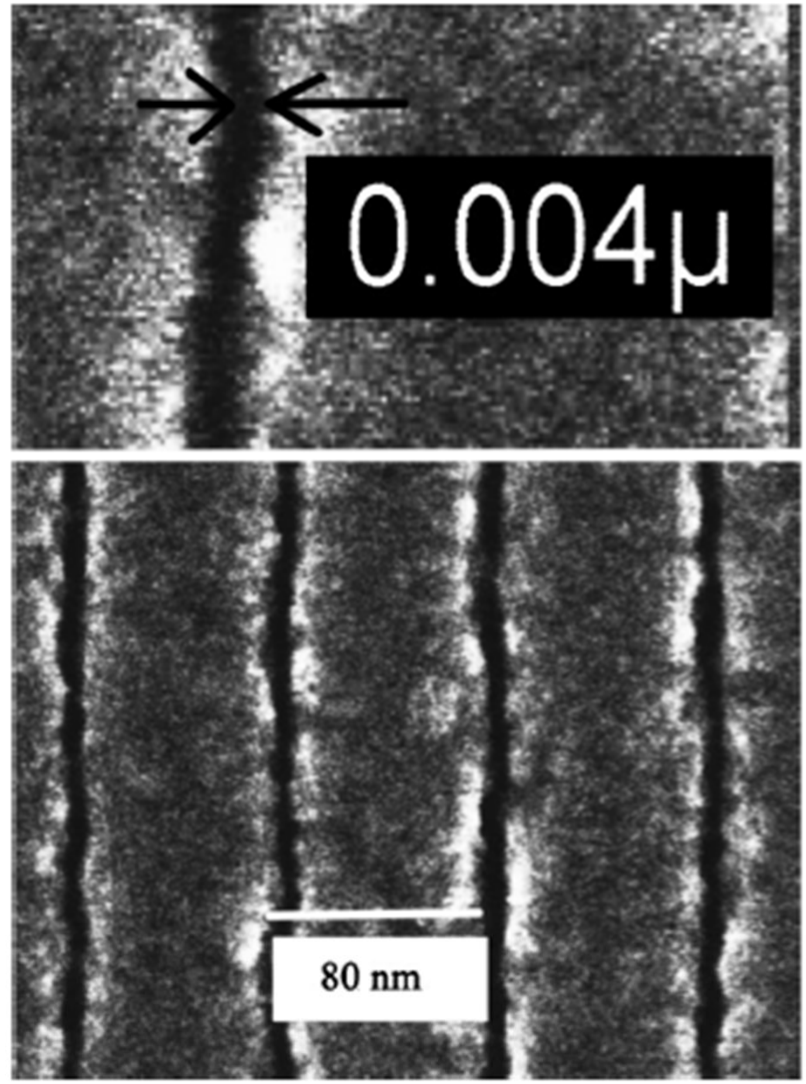


FIG. 3. SEM image of an 80 nm pitch grating in PMMA coated with a thin layer of evaporated Cr to avoid sample charging, taken at 30 kV using sub-pA probe currents. Above shows a magnified view of a section of 4 nm wide line with the image capture software measuring tool, and below shows a wide area view. SEM magnification calibration was carried out using standard samples of known size.

APL **78** (2001) 2762

E-Beam

Electron beam Resist PMMA

The sensitivity depends on the molecular weight

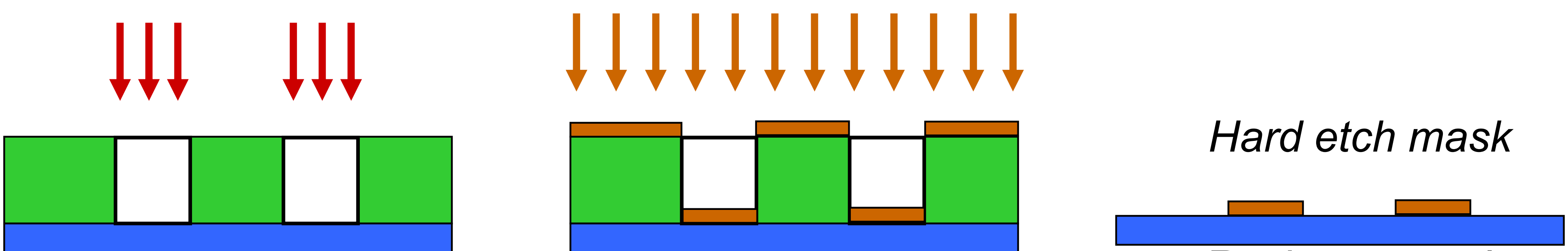
➔ Taking **High molecular weight** results in <u>lower sensitivity</u> as more bonds have to be broken to reach a point where developers can dissolve exposed PMMA.

➔ But it has better contrast and resolution performance!

➔ Also developers can influence the performance of PMMA.

<u>Different PMMA developers have different characteristics ie smaller structures or faster development</u>

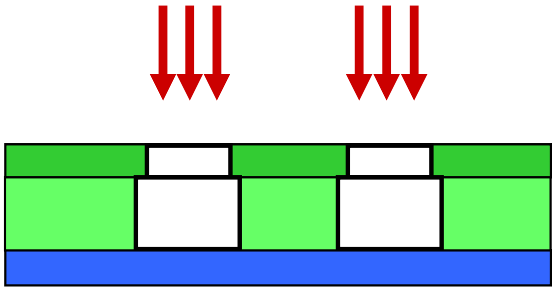
Because of the poor etch resistance of PMMA, it is <u>not suitable as a dry etch</u> mask and is mainly used as a mask for **<u>metal lift off</u>**, ie transfer a PMMA pattern into a metal pattern.



E-beam writing + development | Metal evaporation | Resist removal

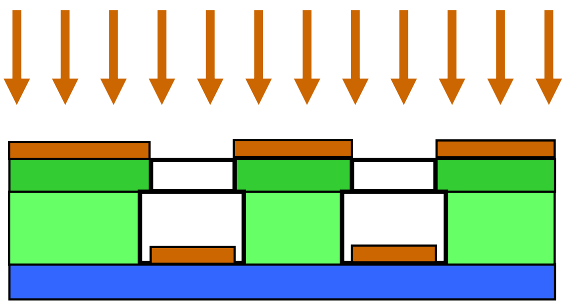
E-Beam

PMMA Resist



E-beam writing + development

Top layer has **high molecular** weight
Bottom layer **low molecular** weight



Metal coating

➔ Bottom layer is more sensitive and will produce wider structures as viewer bonds have to be broken to render it developable!

Resist removal

This will result in better lift off !

E-Beam

Resists

PMMA <-> SU-8

For a 50 keV Electron Beam exposure we need:

3.6 μC/cm^2 for SU-8 exposure (Chemical amplification)
&
500 μC/cm^2 for PMMA exposure

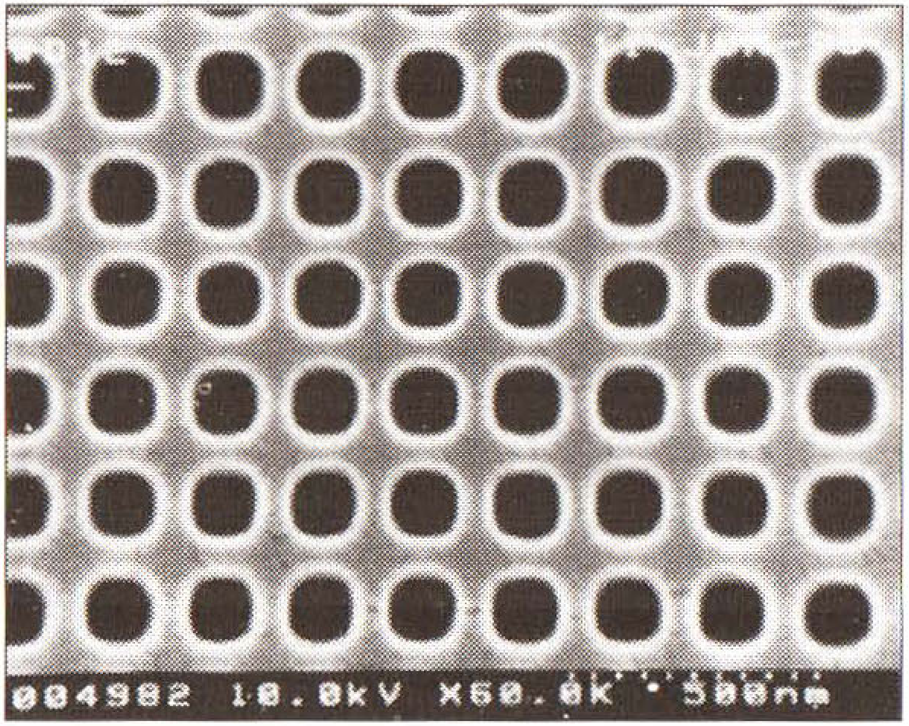
Microelectronic Engineering - Proceedings of the 29th international conference on micro and nano engineering
Volume 73-74 Issue 1, June 2004 Pages 233-237

How many electrons are needed in 1 cm^2? In 100x100 nm^2?

E-Beam

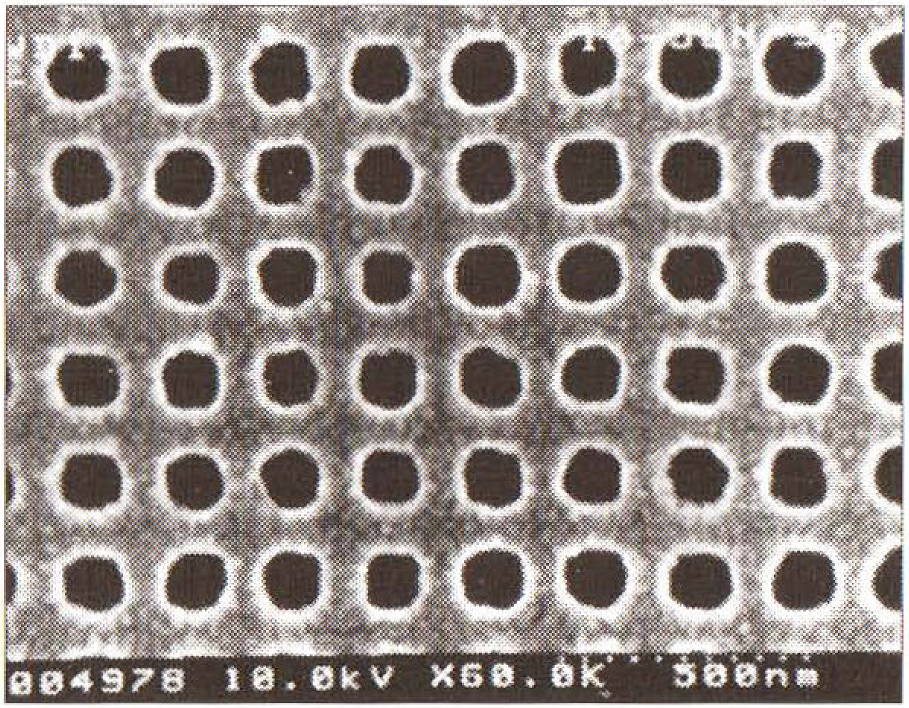
Chemically amplified resists (CARs)

PMMA



(a) 100 nm holes in PMMA (1,450 $\mu C \cdot cm^{-2}$)

AZPF 514



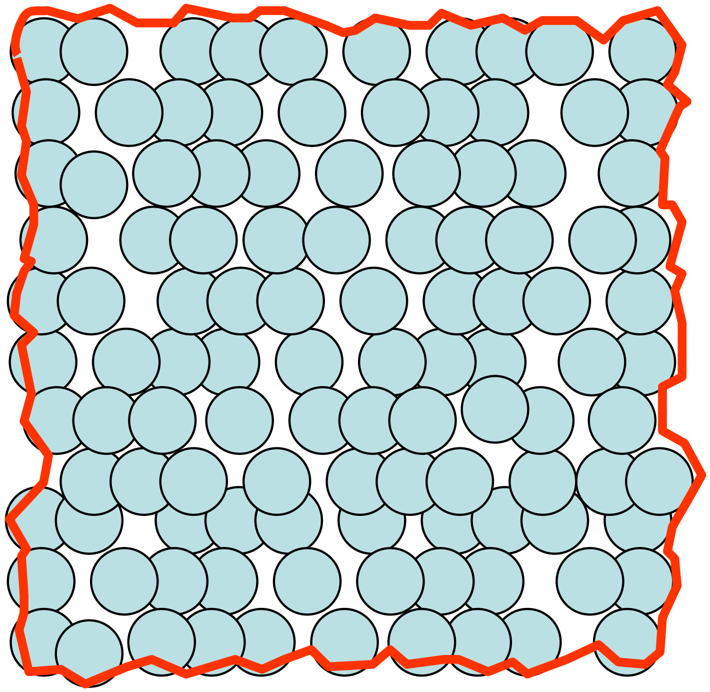
(b) 100 nm holes in AZPF 514 (25 $\mu C \cdot cm^{-2}$)

Fig.3.26. Comparison of sensitivities between PMMA and positive tone chemically amplified resist AZPF514 for 100 nm hole array

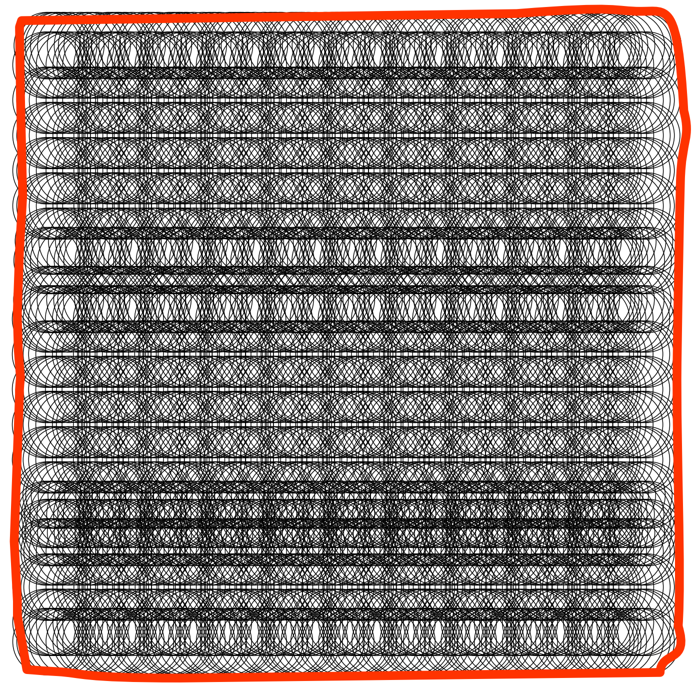
Why are the holes in PMMA more uniform?

E-Beam Shot Noise

CAR Resist



Standard resist



CAR Sensitive resist with low dose exposure

Standard resist with adequate dose exposure

E-Beam
PEB temperature vs resist profile

PEB (post exposure bake) is the most critical step in the <u>CAR</u> process

<u>Variation in PEB temperature</u> can directly influence the **<u>exposure sensitivity</u>** and **<u>resolution!</u>**

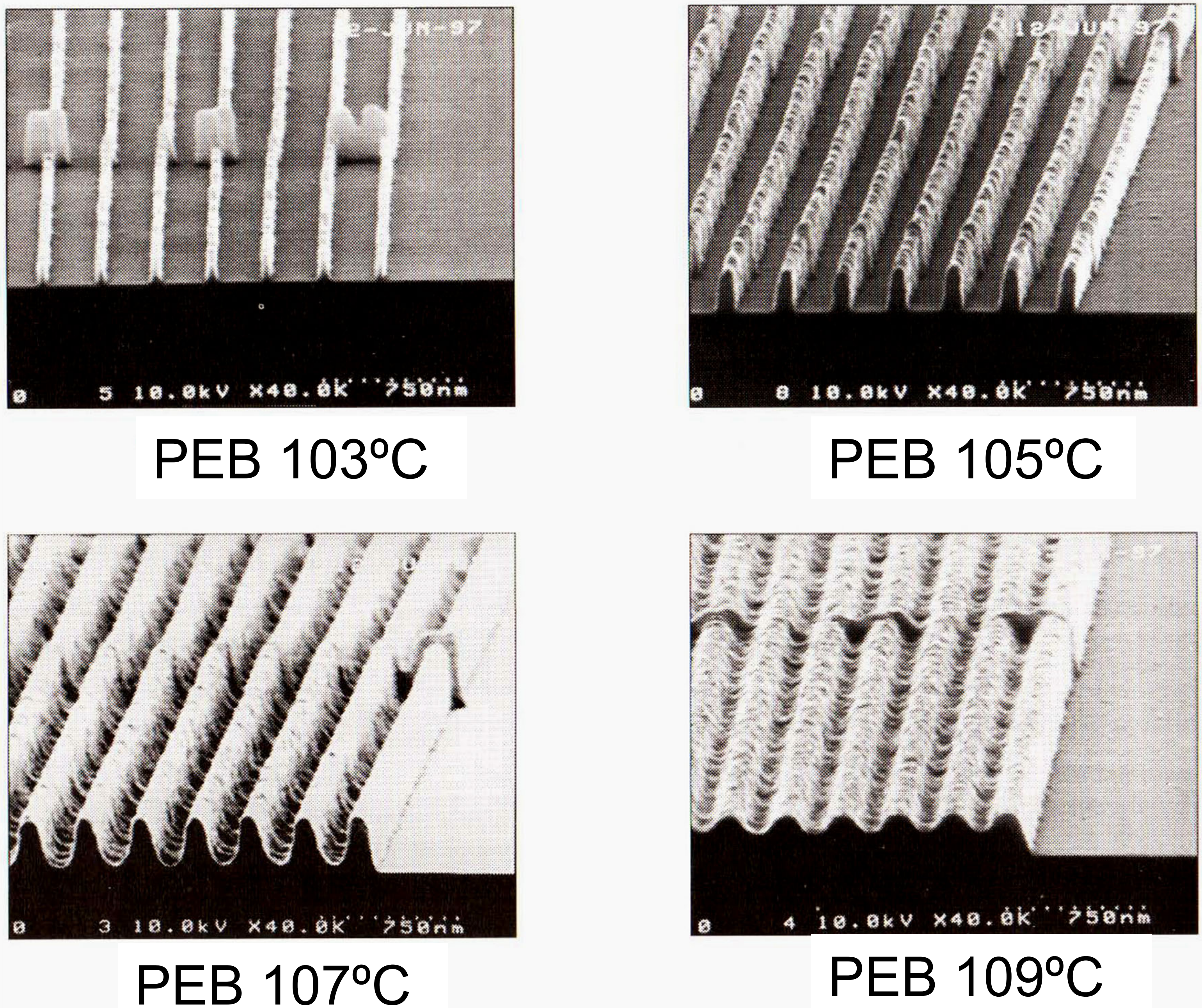


Fig.3.29. The influence of PEB temperature variation on AZPN114 sensitivity

E-Beam
PEB delay vs resist profile

- Not only PEB temperature but also delay before PEB and after exposure can greatly influence the result!
- In some resists the chemical amplification starts before PEB.
- This is extremely important if you realize writing a large area with an e-beam writer could take 10-20 hours sometimes even DAYS!

Issues to consider:

- Beam heating
- Reactions with airborne molecules, such as ammonia or amines, neutralize acid near the top of the resist film, forming a mushroom cap.
- Reactions with certain substrates, such as TiN, neutralize acid near the bottom of the resist, forming a foot.

Why do you think Ti is used?

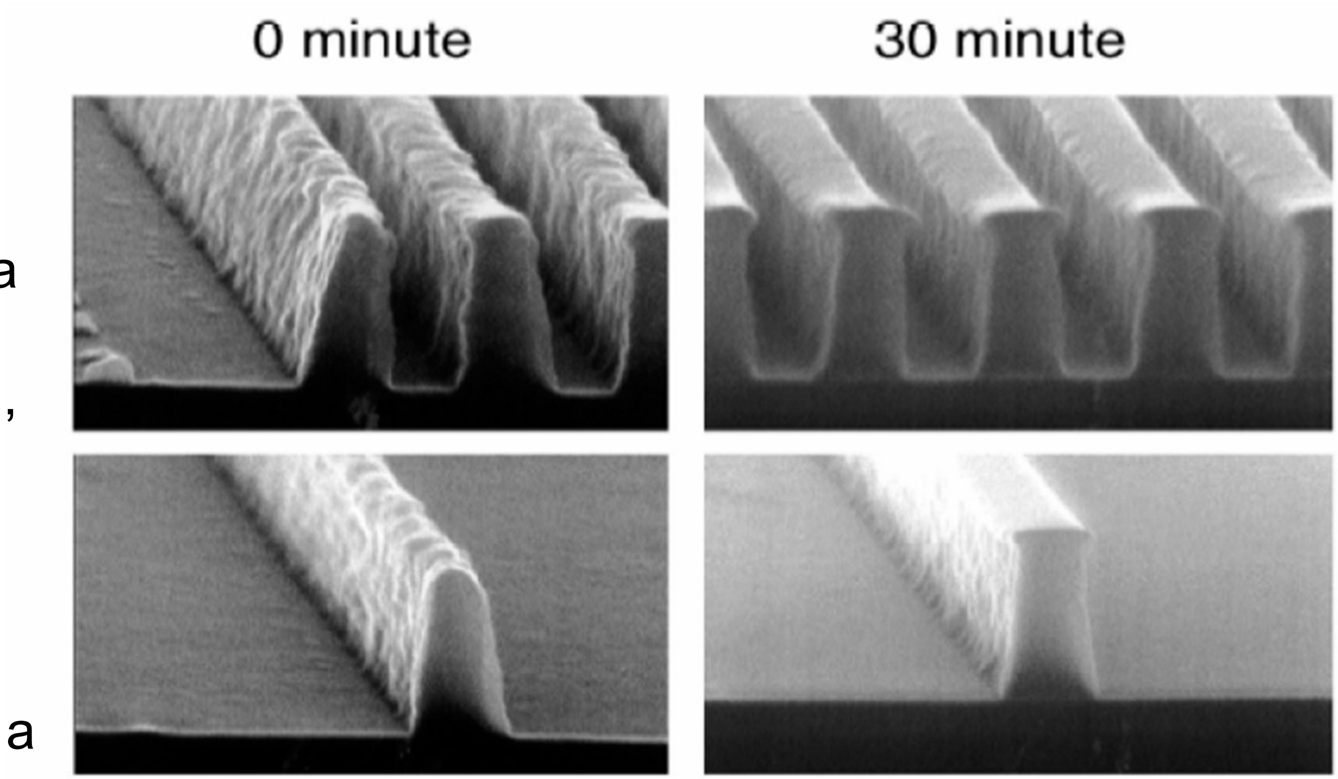


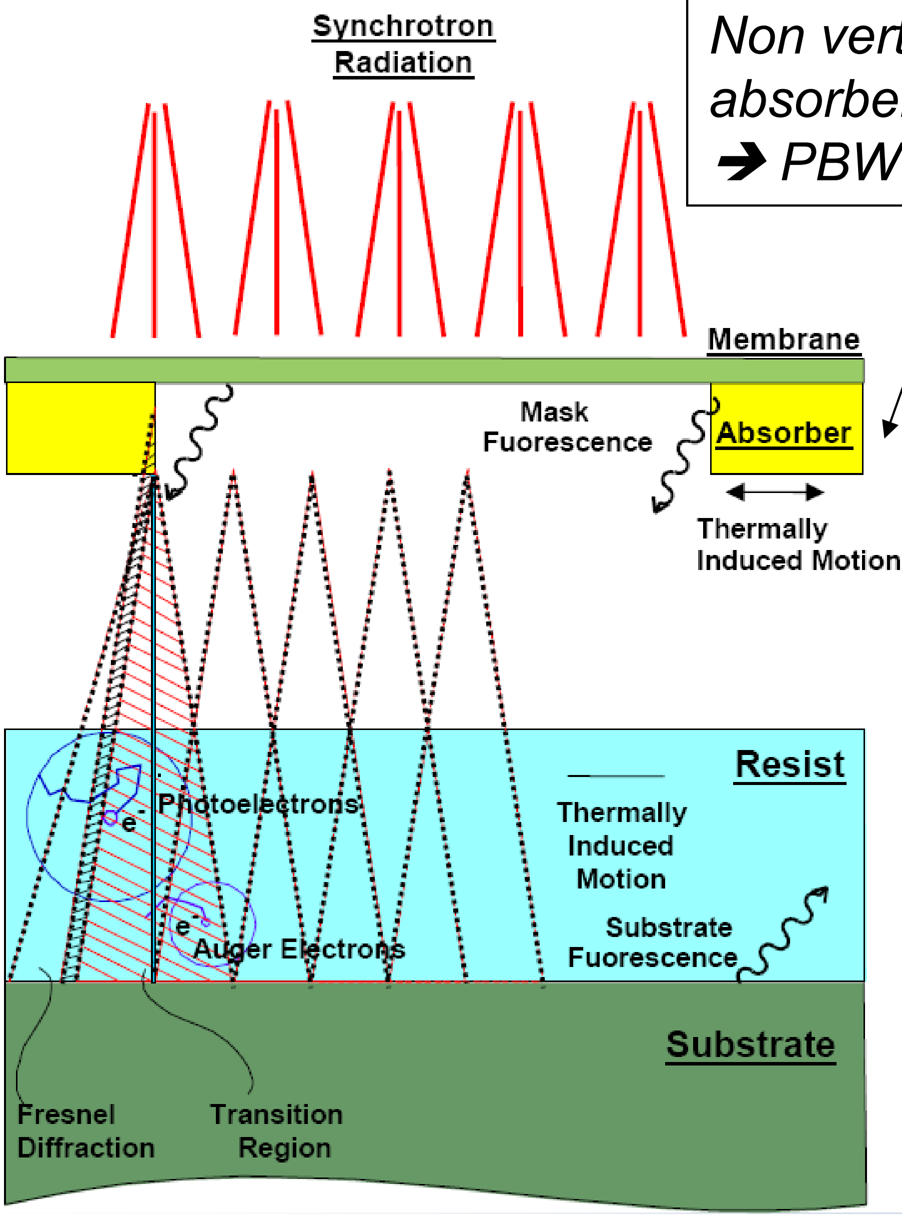
Figure 13. PEB delay effects on acrylate resist #3 on AR19 BARC (820 A). Ammonia concentration = 0.6ppb, N-methyl pyrilldone (NMP) concentration = 0.08ppb.

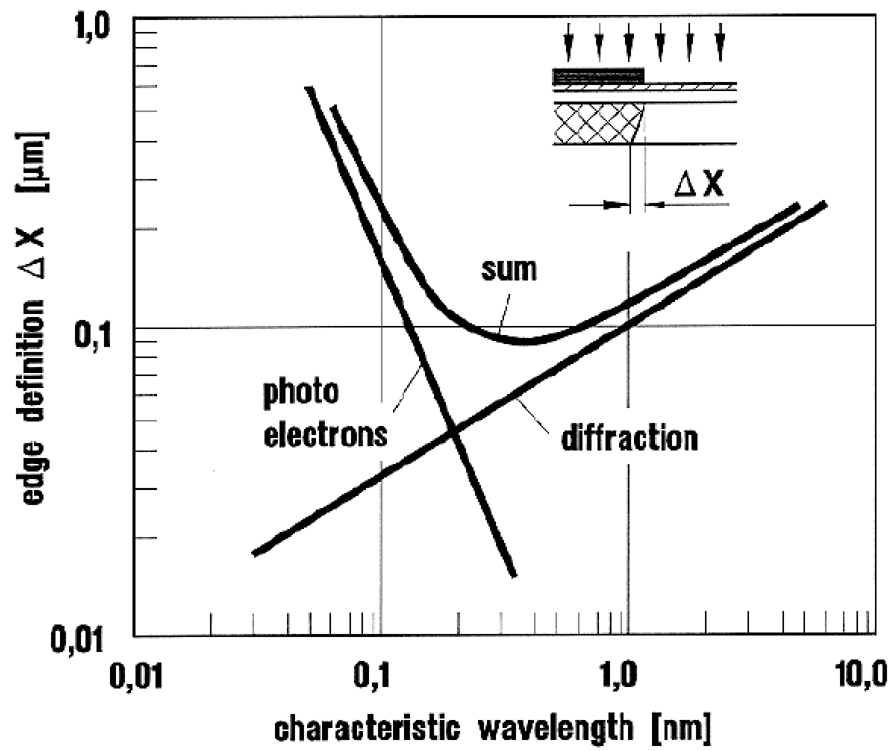
X-ray Lithography

Accuracy of Lithography with nm Photons

Divergent angle of the X-ray beam 0.1-1mrad

Non verticality of the absorber side wall
➔ PBW is superior!



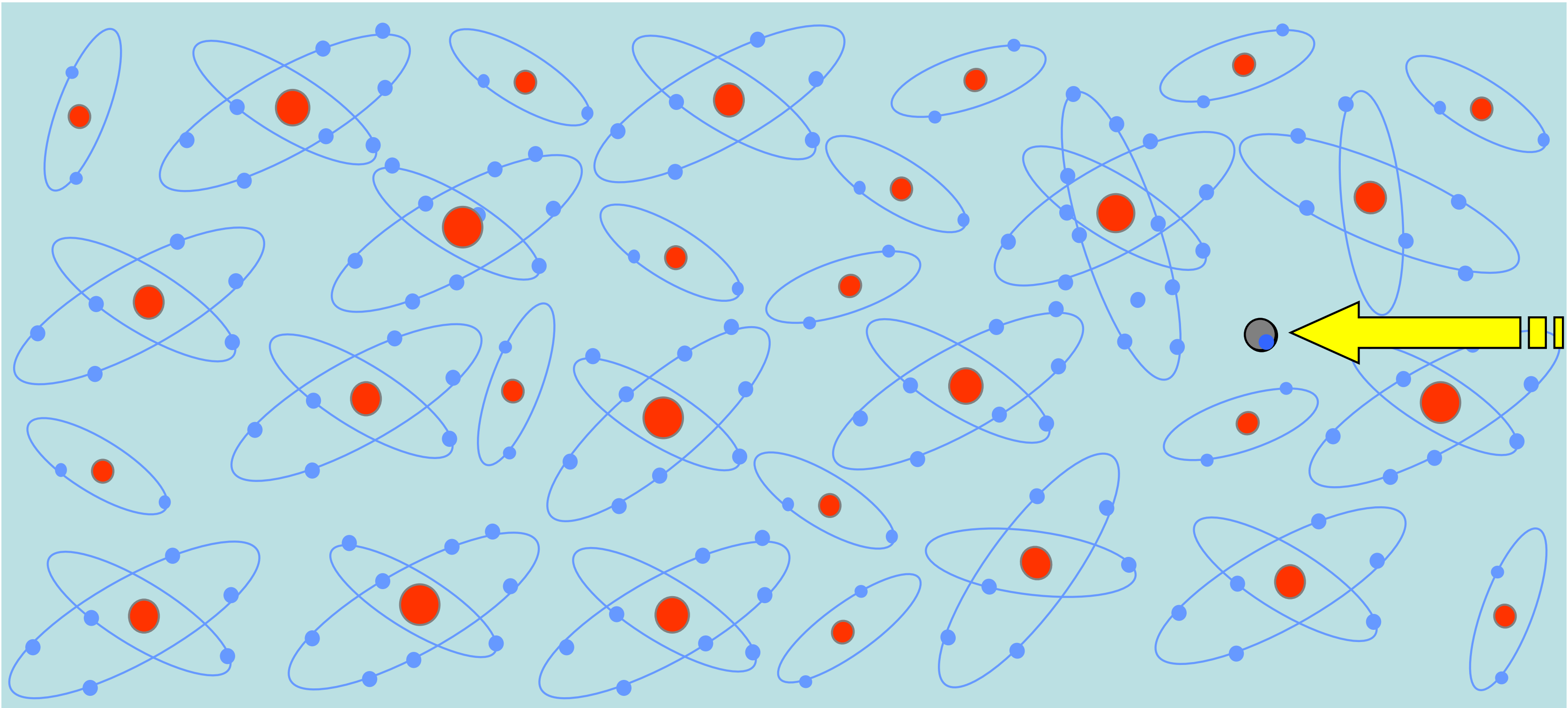


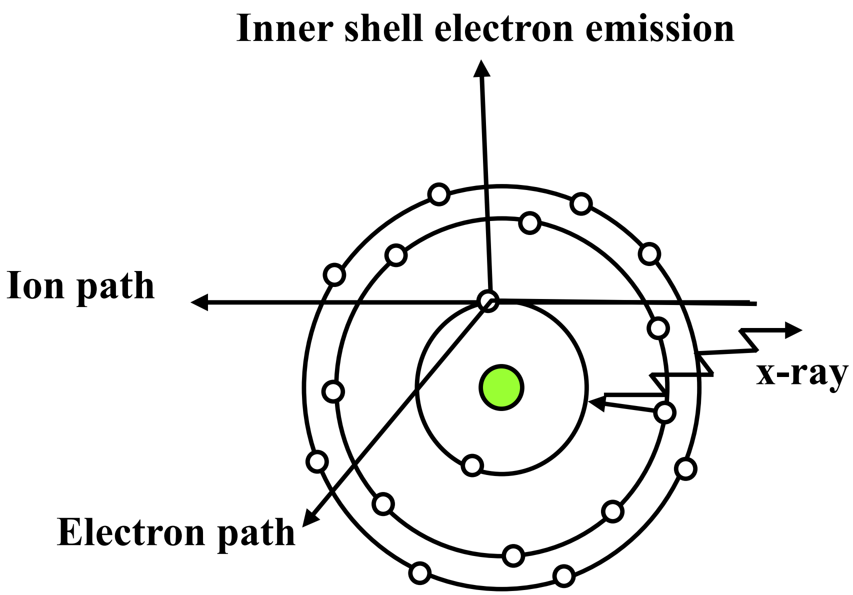
1) Fresnel diffraction
2) Range of photo electron (~ keV)

Substrate induced secondary electrons & X-rays can cause unwanted exposure at the foot of your structures!
➔ Proximity effect!

E-Beam / Ion Beam

Fast Ion and Electron interactions with materials





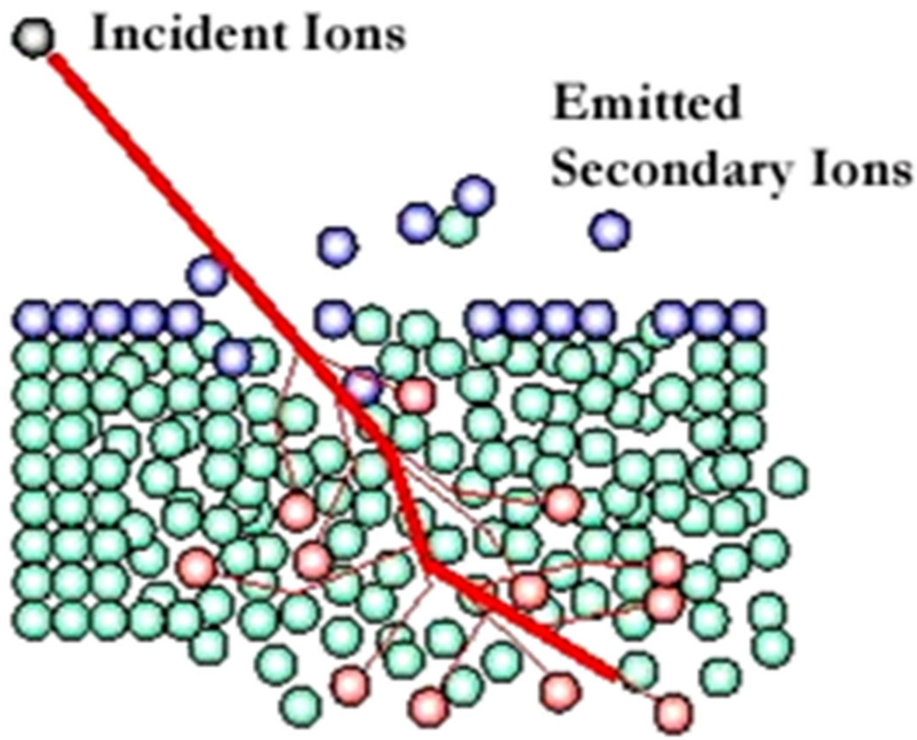
These scattering events deposit energy in the sample (which is responsible for the lithography) and give you “information” about your specimen (eg induced x-rays or nuclear scattering)

SIMS

SIMS: Secondary Ion Mass Spectrometry FIB: Focused Ion Beam technology

Here we use Low energy heavy ions!

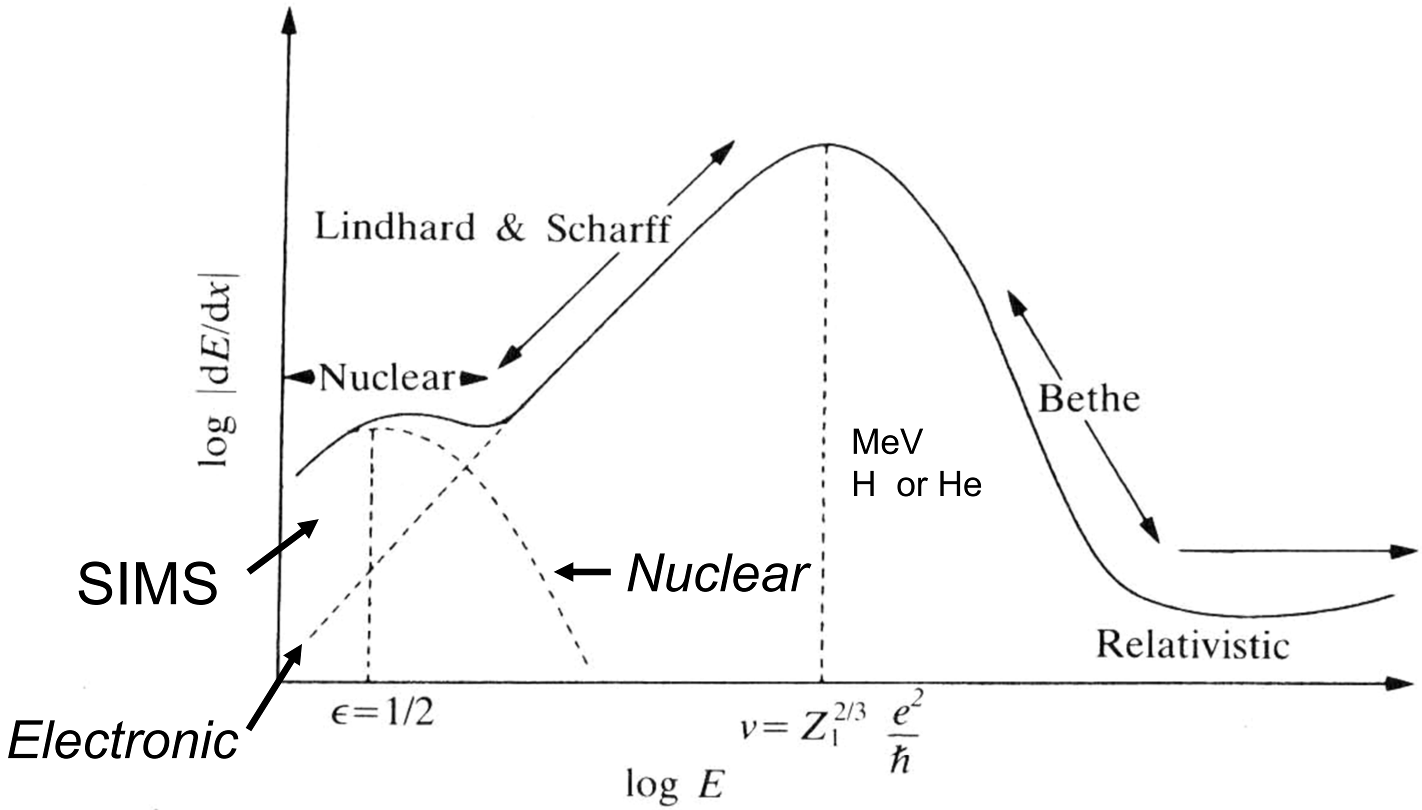
- SIMS is a surface analysis technique used to characterize the surface and sub-surface region of materials.
- It effectively employs the ***mass spectrometry*** of ionised particles which are emitted when a solid surface is bombarded by energetic primary particles (some keV).
- The primary particles may be electrons, ions, neutrals or photons.



SIMS

Stopping of energetic ions

Nuclear ⇔ Electronic



$$\varepsilon = \frac{aEM_2}{Z_1 Z_2 e^2 (M_1 + M_2)}$$

a; Thomas Fermi screening radius

FIG 3.6. Schematic diagram of the stopping power of an ion as a function of energy. At low velocities nuclear stopping dominates for medium and heavy ions. At higher velocities electronic stopping takes over and the projectile is preferably neutral. Beyond the stopping-power maximum the Bethe regime is approached where the projectile is preferably stripped.

SIMS

Energy deposition leads to

in nuclear stopping regime

Change of lattice structure

Loss of surface material

- Electrons
- Photons
- Particles (atoms + molecules)
  - (Un)charged possibly excited

All emitted with certain angular distribution

This phenomenon is used in **SIMS** analysis of substrates

If we understand the scattering process
➔Our measurements will tell us the sample composition!

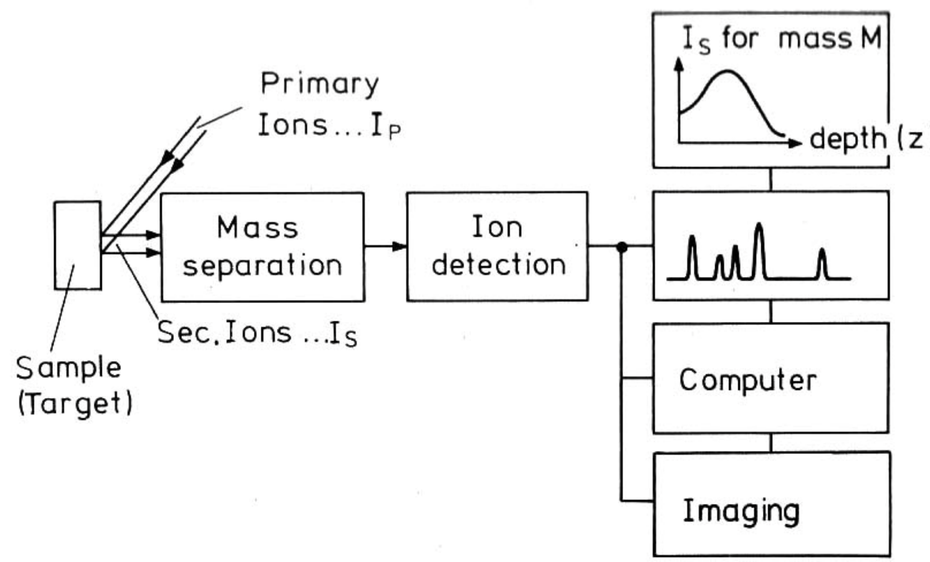


Fig. 1.1. Principle of SIMS. Reproduced with permission of Werner [1713], *Proceedings of the Conference on Electron and Ion Spectroscopy of Solids*, L. Fiermans et al. (Eds.), Ghent 1977 and the Plenum Publishing Corporation 1978, p. 325.

SIMS

Static SIMS:

Provides information from uppermost monolayer ”virtually” without disturbing its composition & structure ~ 10^{-9} A/cm^2 (it will take ~ 10,000 s for a monolayer to be removed)

- Typical pressure of 10^{-10} mbar is needed*

* Due to left over molecules one monolayer will form in 1 s at a pressure of 10^{-6} mbar

- E/M analyser with high overall transmission for ions originating from a large area
  ➔ Quadrupoles are used

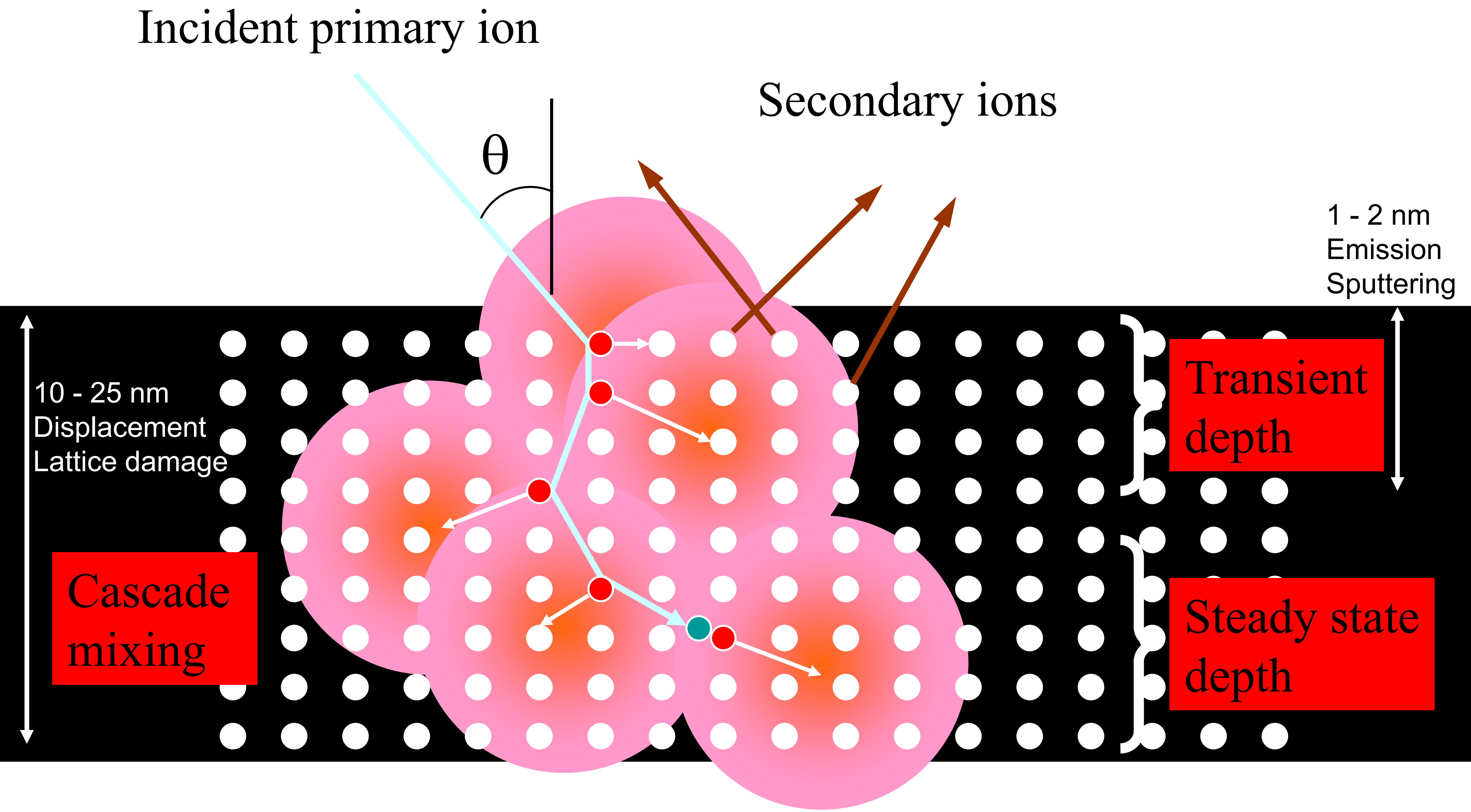
Dynamic SIMS:

High current densities (~A/cm^2) monolayer lifetime ~ms
Higher pressure can be allowed
Depth profiling (sensitivity ~ppb range)
With focused ion beam ➔ 3D analysis

Depending on the application
different kinds of mass spectrometers (e/m) are used

SIMS

Collision Cascade



SIMS

The Sputtering Process

- The process of sputtering can be described by the principles of classical mechanics through binary collisions of primary ions with single target atoms.
- Depending on the energy range of the primary particle, elastic and inelastic collisions take place. Dominating interactions in the **keV** range are ***elastic collisions***. They can be described by a value known as ***nuclear stopping power*** which is defined by the energy loss of the primary particle per path length:

$$\left(\frac{dE}{dx}\right)_n$$

    - Nuclear stopping contributes to the collision cascade.

- The number of inelastic collisions increases with rising energy. ***Inelastic collisions*** dominate in the **MeV** energy range. The corresponding value to describe this interaction is the ***electronic stopping power***.

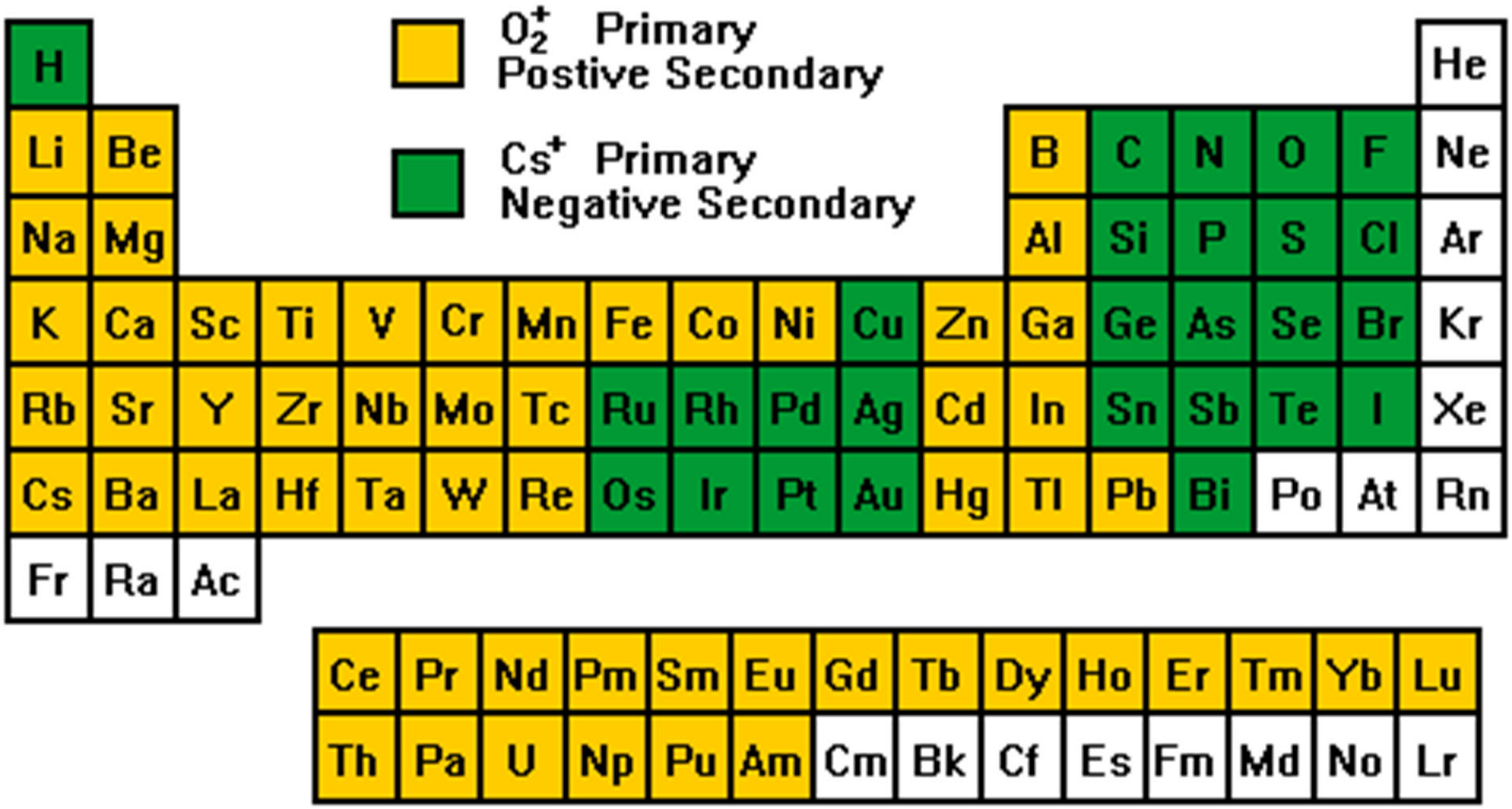
$$\left(\frac{dE}{dx}\right)_e$$

SIMS

Secondary Ion Yields
- Primary Beam Effects

- Other factors affecting the secondary ionization efficiencies in SIMS:
  - ***Oxygen bombardment*** increases the yield of **positive ions**
  - ***Cesium bombardment*** increases the yield of **negative ions**.

  The increases can range up to four orders of magnitude.



SIMS

Primary Ion Sputter Yields in Al

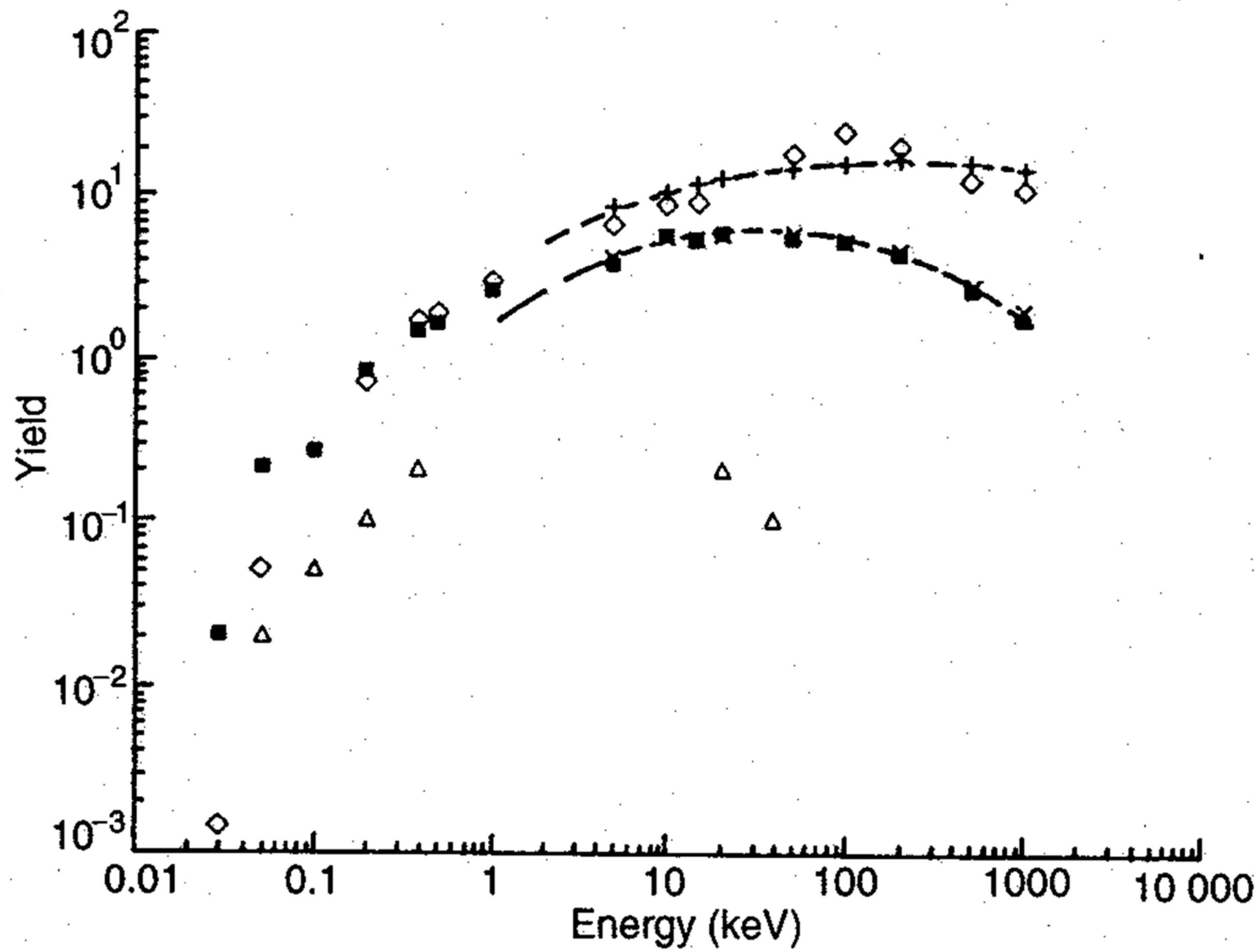


Figure 5.2. Experimental sputter yield data for aluminium as a function of primary ion energy for a number of different primary ions: Δ, He; ◊, Xe; ▯, Ar; +, Xe (theoretical); x, Ar (theoretical)

SIMS

Positive Secondary Ion Yields

O_2^+ bombardment

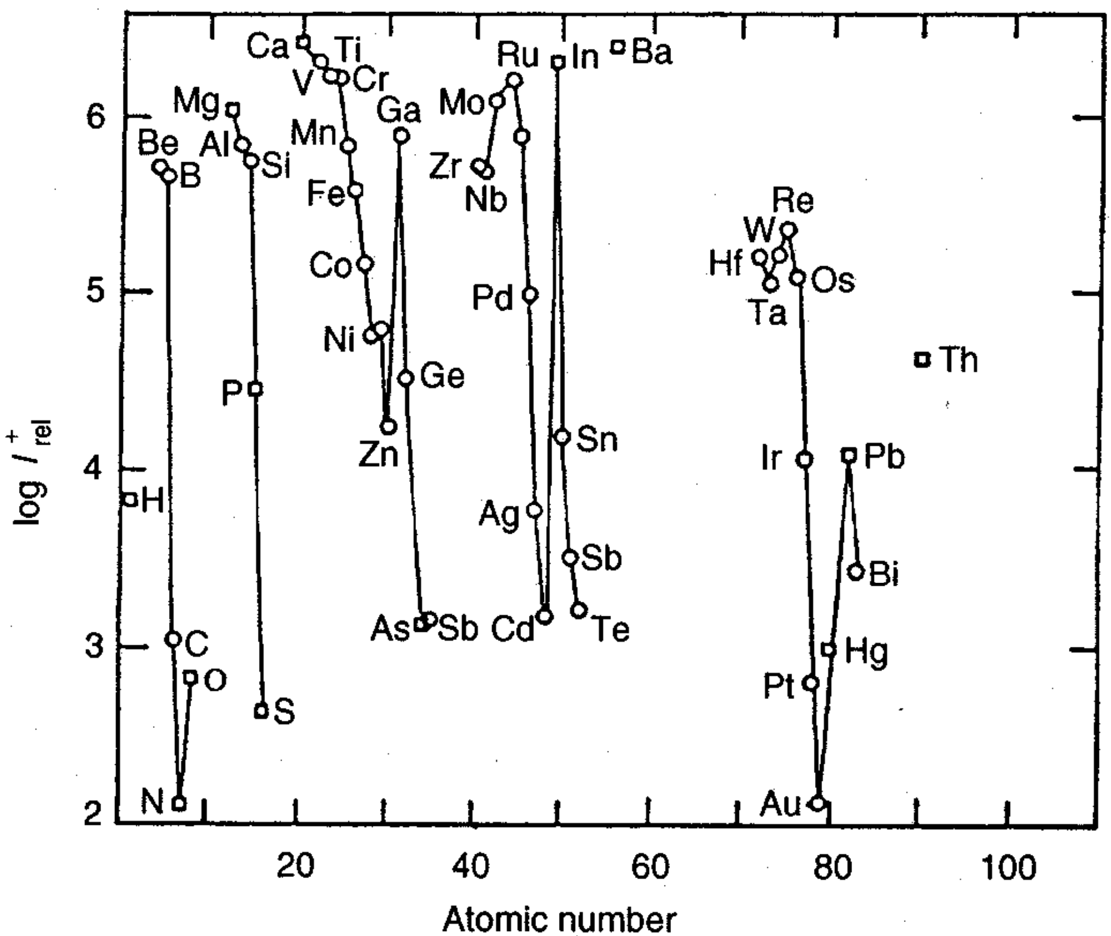


Figure 5.3. The variation of positive ion yield as a function of atomic number for 1 nA 13.5 keV O-bombardment: o from elements; ▯, from compounds. Reproduced with permission from H.A. Storms, K.F. Brown, and J.D. Stein, *Anal. Chem.*, **49**, 2023 (1977). (Copyright (1977) American Chemical Society

SIMS

Negative Secondary Ion Yield

Cs^+ bombardment vs M^+ ion yield for O^-

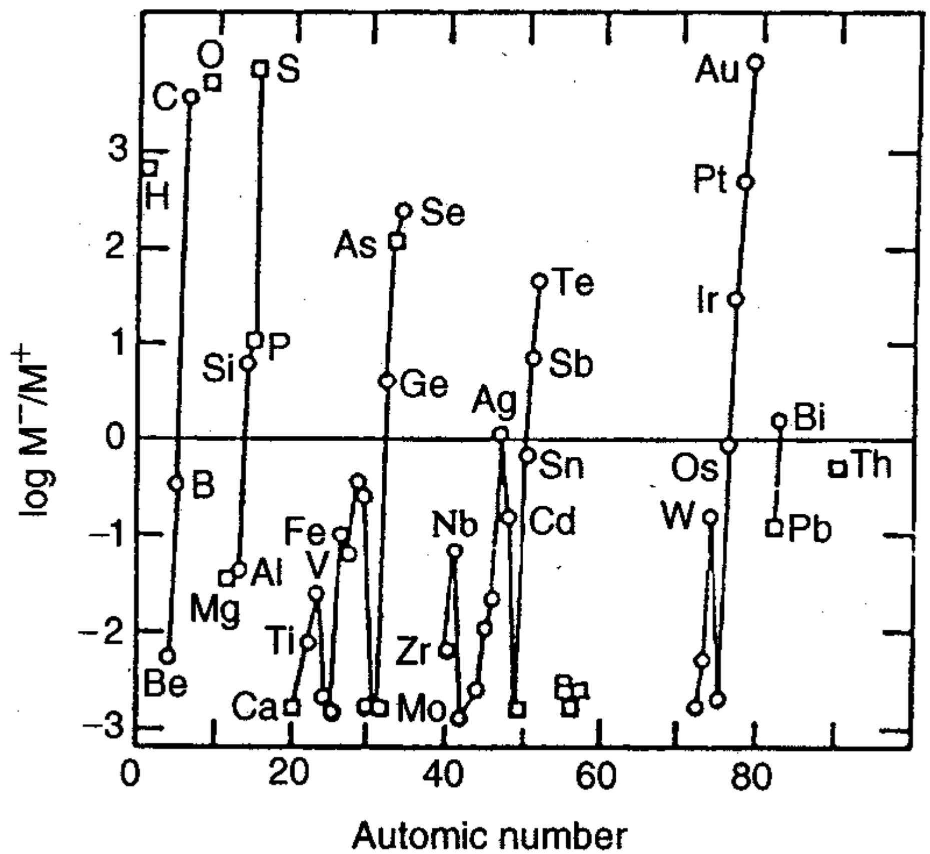


Figure 5.30. The ratio of negative ion yield (M^-) under Cs^+ bombardment to positive ion yield (M^+) under O^- bombardment as function of atomic number. Reproduced from data in H.A Storms, K.F. Brown, and J.D. Stein, *Anal. Chem.*, **49**, 2023. Copyright (1977) American Chemical Society