PC3242 Part II Lectures 3

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)		6, 7 & 8
SIMS	Extra material provided	
FIB in Lithography	Chapter 4	
High Energetic Ions (MeV)	Extra material provided	9
RBS	Extra material provided	10
Light ions in lithography	Extra material provided	11
Nano Imprint Lithography	Chapter 7	12
3DP Three Dimensional Printing	Extra material provided	13
Etching	Chapter 6	14

JA van Kan 2024

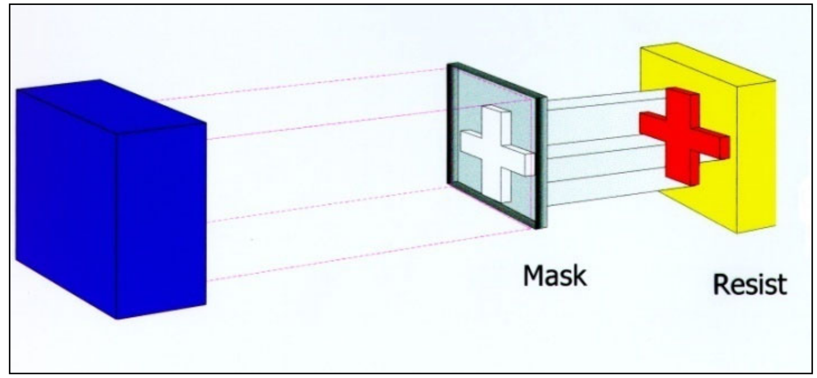
Optical Lithography

Masked processes (electromagnetic)

- Light (Coherent)
- X-rays, UV

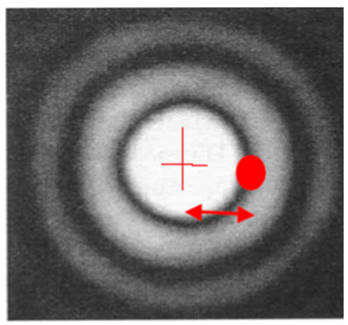
Contact

$$w = k\sqrt{\lambda z}$$



Projection printing

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

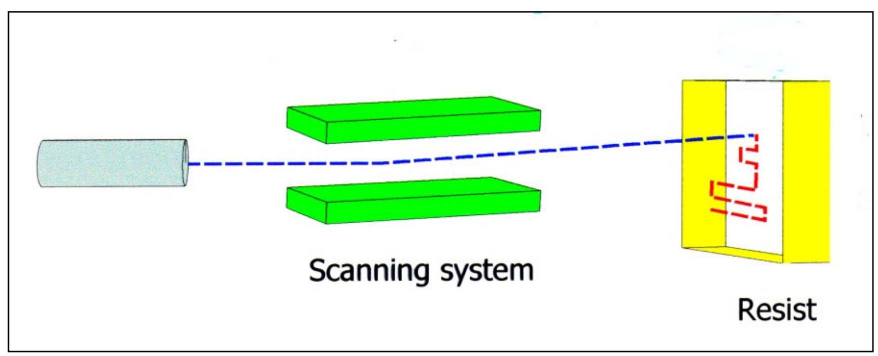


$$DOF = k_2 \frac{\lambda}{(NA)^2}$$

Coherence σ is a critical parameter here to achieve ultimate resolution

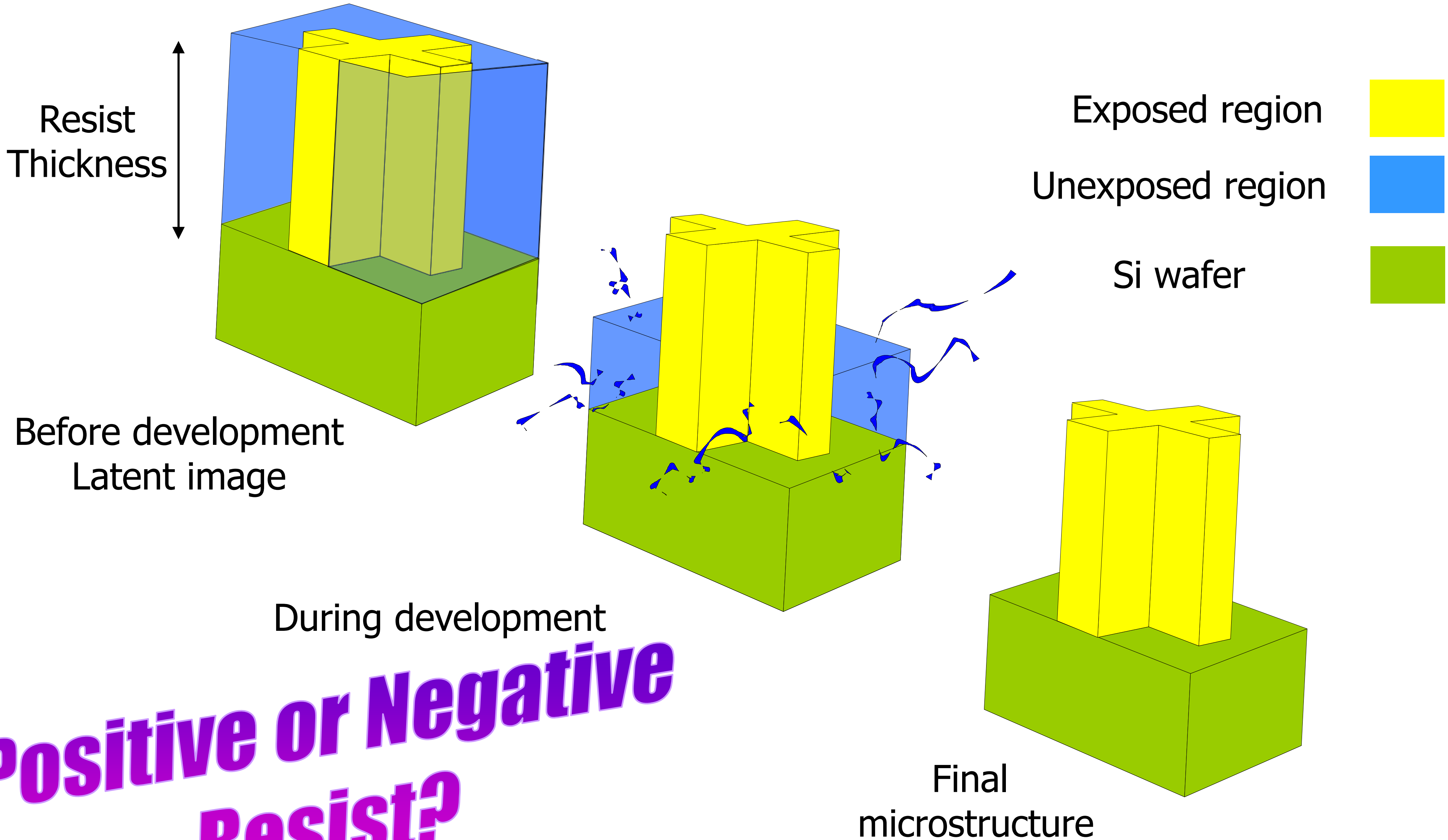
Direct write processes

- Charged particles



Optical Lithography

Chemical development

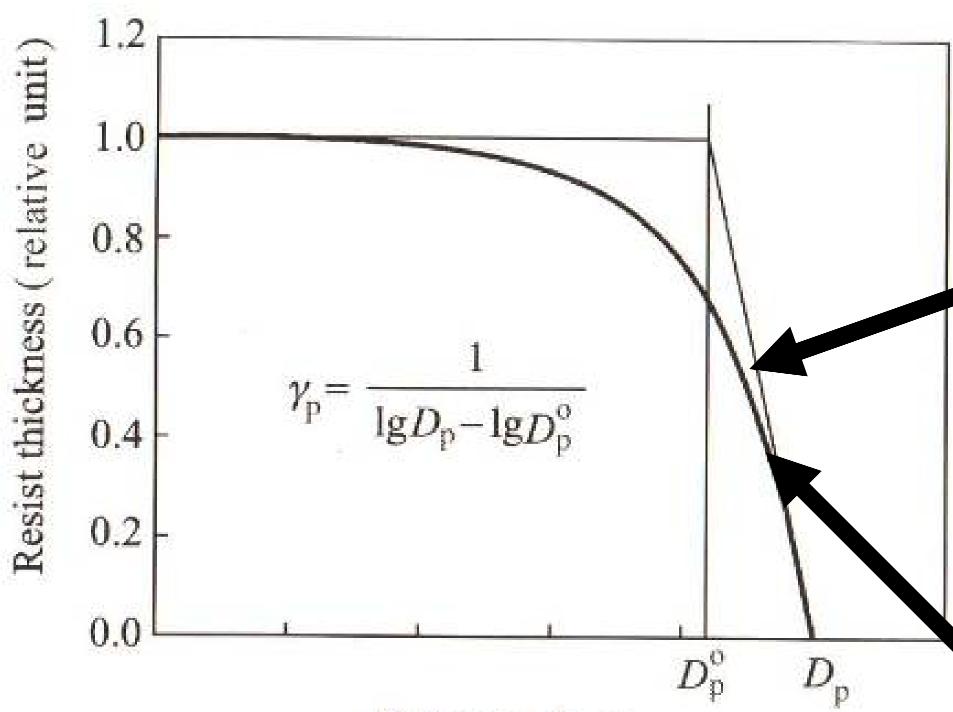


Positive or Negative Resist?

Optical Lithography

Grey-scale

Optical lithography can also produce curved resist profiles; How?



D_p^o threshold dose D_p sensitivity γ_p contrast

(a) Sensitivity and contrast for positive photoresists

➔Using grey scale lithography

In electron beam you can vary the energy deposition per unit area in combination with a **<u>low contrast</u>** resist this give nice control over resist thickness.

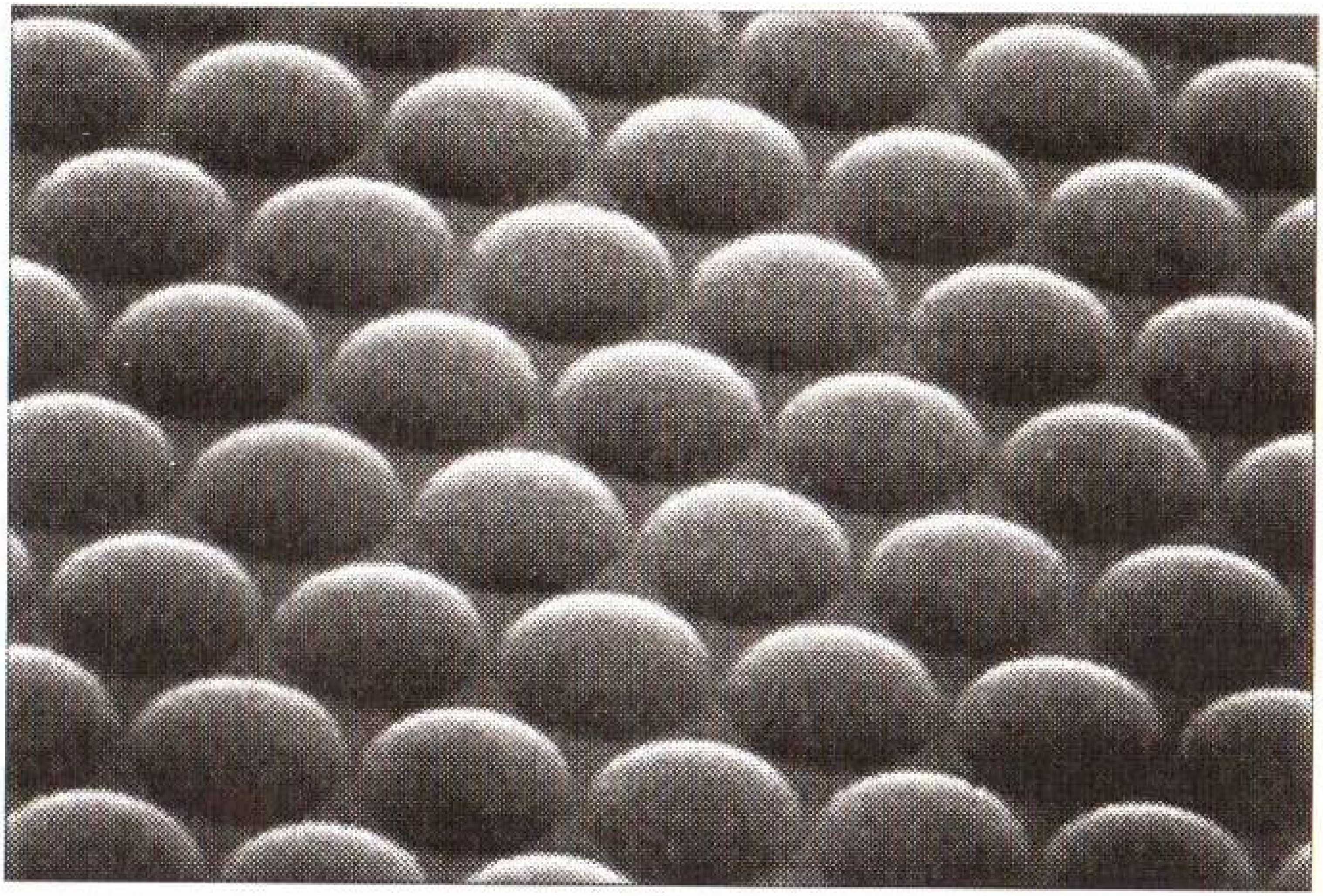
In optical lithography we need grey scale masks + **<u>low contrast</u>** resist.
Mask requirements:
Opaque pixels in transparent area or transparent pixels in opaque areas
Here the pixel size < resolution

➔ Transparency modulation

Optical Lithography

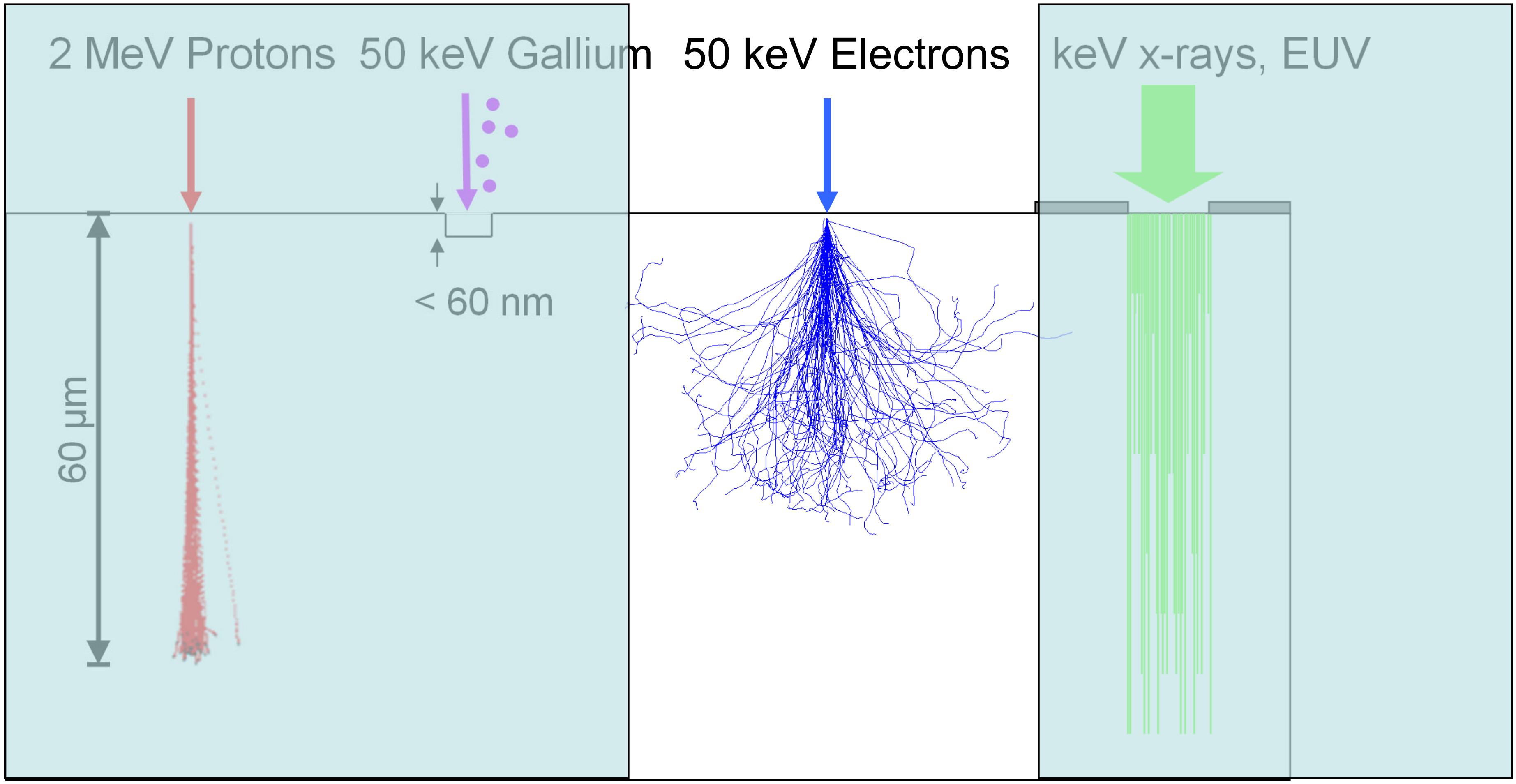
Grey-scale

Application of grey scale lithography can be found in the area of integrated optics:



Micro lens array made by photo lithography through a grey scale mask

Particle/wave interaction with material



2 MeV protons: Well defined path + Dose homogeneity

(Focused ion beam FIB): Surface atoms removed by sputtering

50 keV electrons: beam broadening below the surface

X-Rays need mask, well defined path: dose exp decay with depth

- **Nanolithography** using particles or waves can be planned if we understand the physics of the interactions.
  E.g. like in Optical lithography, Electron Beam Writing, FIB and Proton Beam Writing.

Electron Beam Lithography / Microscopy

Other books on electron microscopy:

Scanning Electron Microscopy and X-ray Microanalysis
Joseph Goldstein, Dale E Newbury, David C Joy, Charles E Lyman, Patrick Echlin, Eric Lifshin, LC Sawyer, JR Michael

Transmission Electron Microscopy: A Textbook for Materials Science
DB Williams and C Barry Carter

E-Beam

Introduction

Electron means we use electrons to form our image. Electrons behave as waves just like light, but have a much shorter wavelength.

Microscopy means we are looking at small things

What is electron microscopy?

$$\lambda_{light} = \frac{hc}{E} \geq 157nm$$

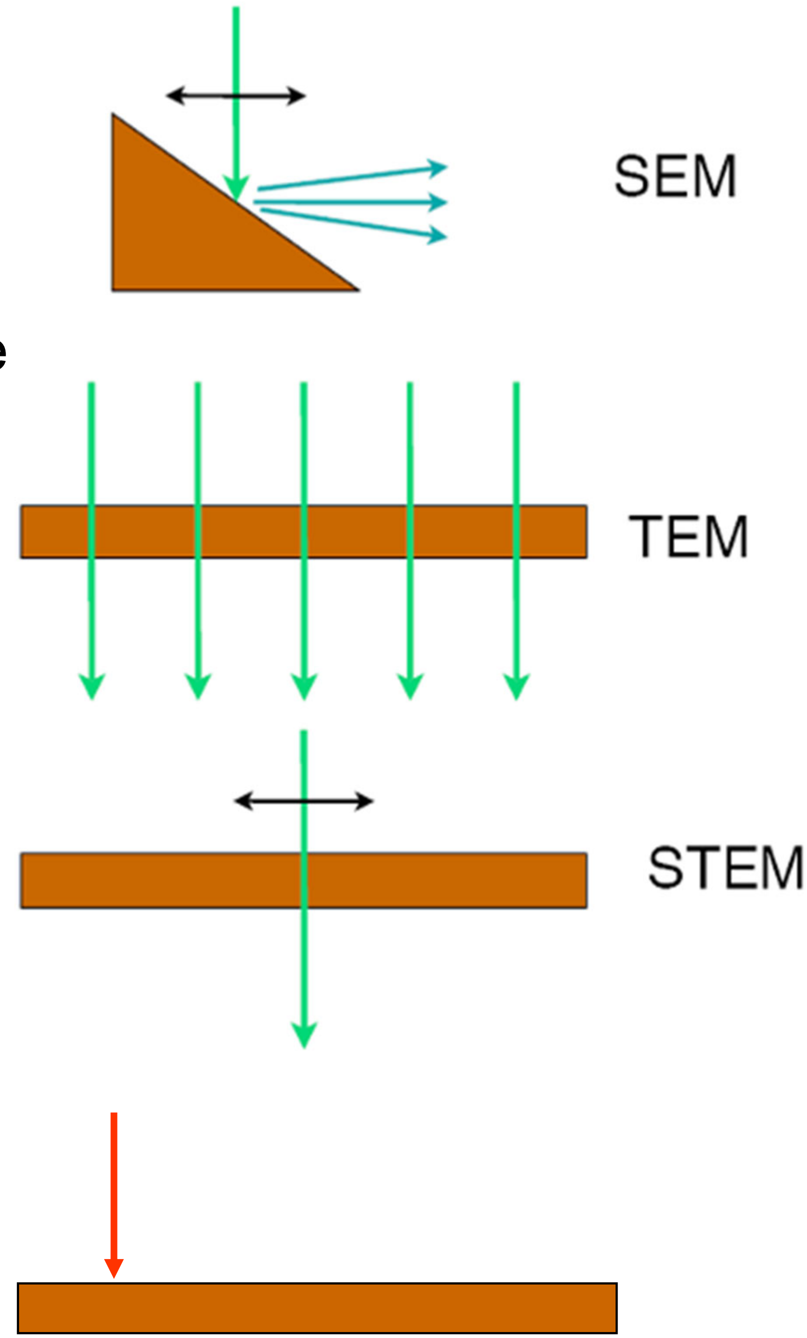
Why use electrons not light?
Electrons have a much shorter wavelength than light. You cannot see anything smaller than half the wavelength of the radiation you are using

$$\lambda_e = \frac{1.226}{\sqrt{V}}(nm)$$

$$=h/p=\frac{h}{m_e v}=\frac{h}{\sqrt{2em_eU}} = \frac{6.63\text{x}10^{-34}}{\sqrt{2\text{x}9.1\text{x}10^{-31}\text{x}10^{3}\text{x}1.6\text{x}10^{-19}}} = \frac{6.63\text{x}10^{-34}}{1.71x10^{-23}} = 3.86\text{x}10^{-11}m$$

E-Beam

Techniques and acronyms



EM: Electron microscopy. Covers TEM, SEM, STEM, etc

SEM: Scanning electron microscopy. Collect the secondary electrons emitted from the surface.

TEM: Transmission electron microscopy

STEM: Scanning transmission electron microscopy. Like TEM, but scan a finely focused beam of electrons across the specimen rather than image using a broad beam

E-beam (e-beam) lithography

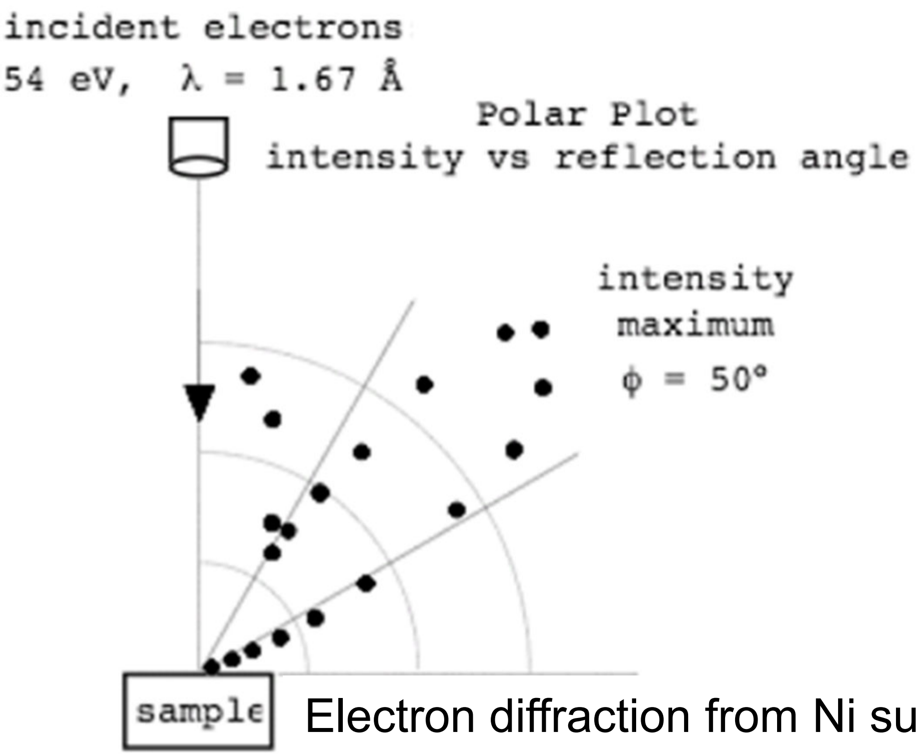
E-Beam History

Optical microscopy: Resolution limited by wavelength of light to ~300nm
Other radiation (X-rays, γ-rays) cannot be focused.

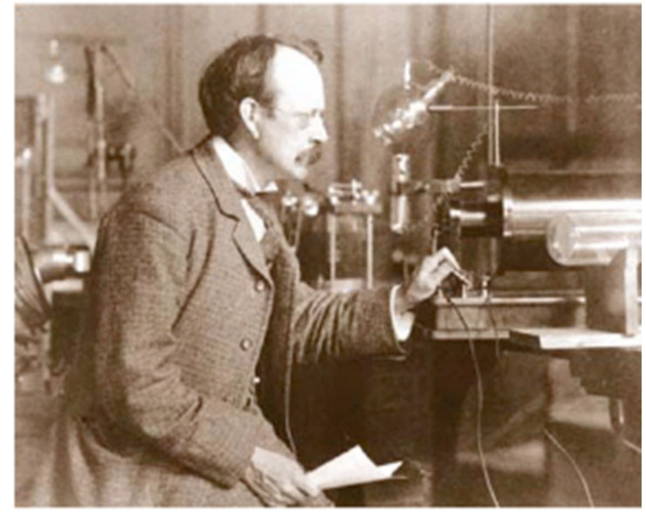
1897: JJ Thompson discovers the electron

1925: de Broglie proposes electrons are waves with small wavelength

1927: Electron diffraction demonstrated by CH Davisson and Lh Germer (reflection) and GP Thompson and A Reid (transmission)



Electron diffraction from Ni surface Davisson and Germer


JJ Thompson, Cavendish Labs

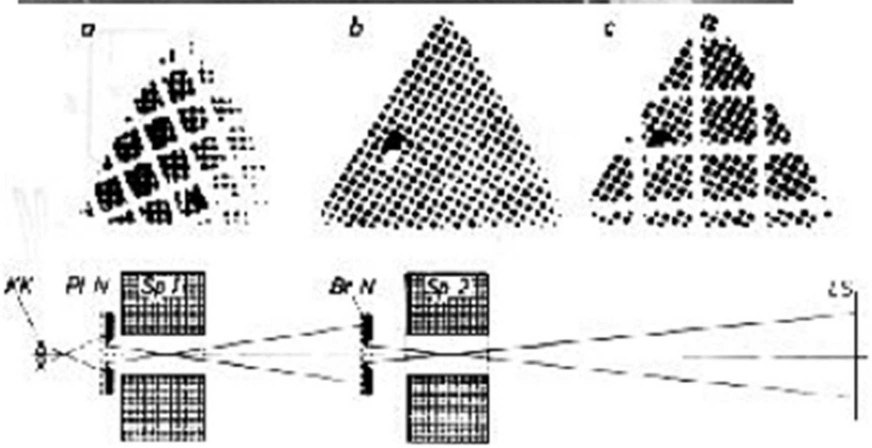

Davisson and Germer

E-Beam History

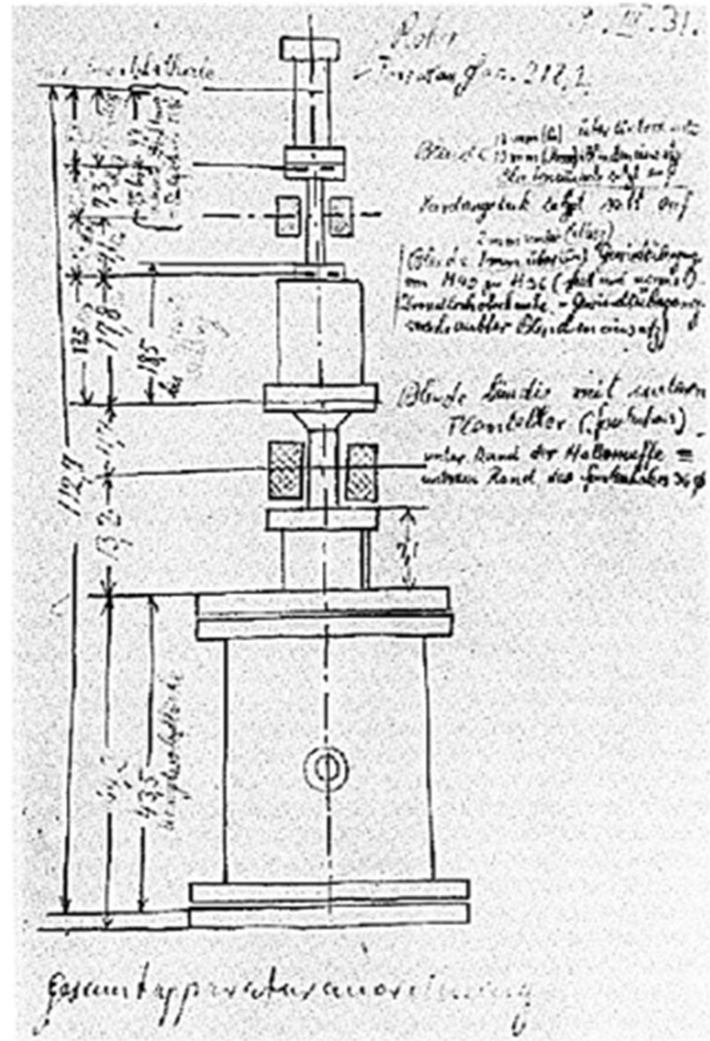
1931: M Knoll and E Ruska build first electron microscope

M Knoll and E Ruska, Das Elektronenmikroskop. Z. Physik **78** (1932) 318–339

Ruska & Knoll, 1931



First TEM image, magnification 17.4×, 50kV



Ruska’s sketch of first TEM

http://ernst.ruska.de/daten_e/library/documents/999.nobellecture/lecture.html

E-Beam History

1934: Resolution of electron microscope better than light microscope – Driest & Muller

1936: First commercial TEM – Metropolitan-Vickers AEI EM1

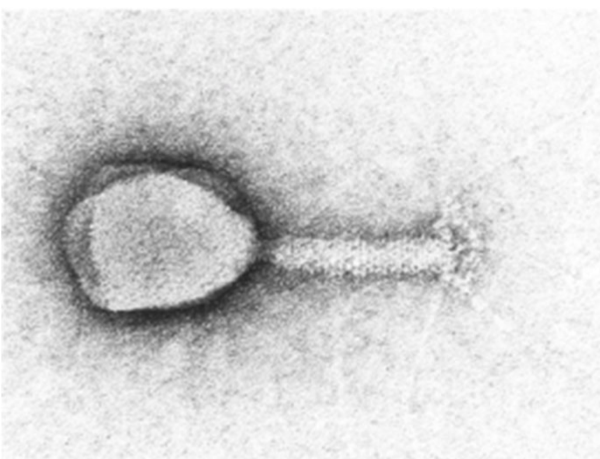
1938: First practical commercial TEM – von Borries & Ruska, Siemens. 10 nm resolution. M von Ardenne builds first STEM

1940: RCA TEM, 2.4 nm resolution

1941: First electron micrographs of viruses

1942: First SEM built by Zworykin et al

1945: Resolution 1 nm

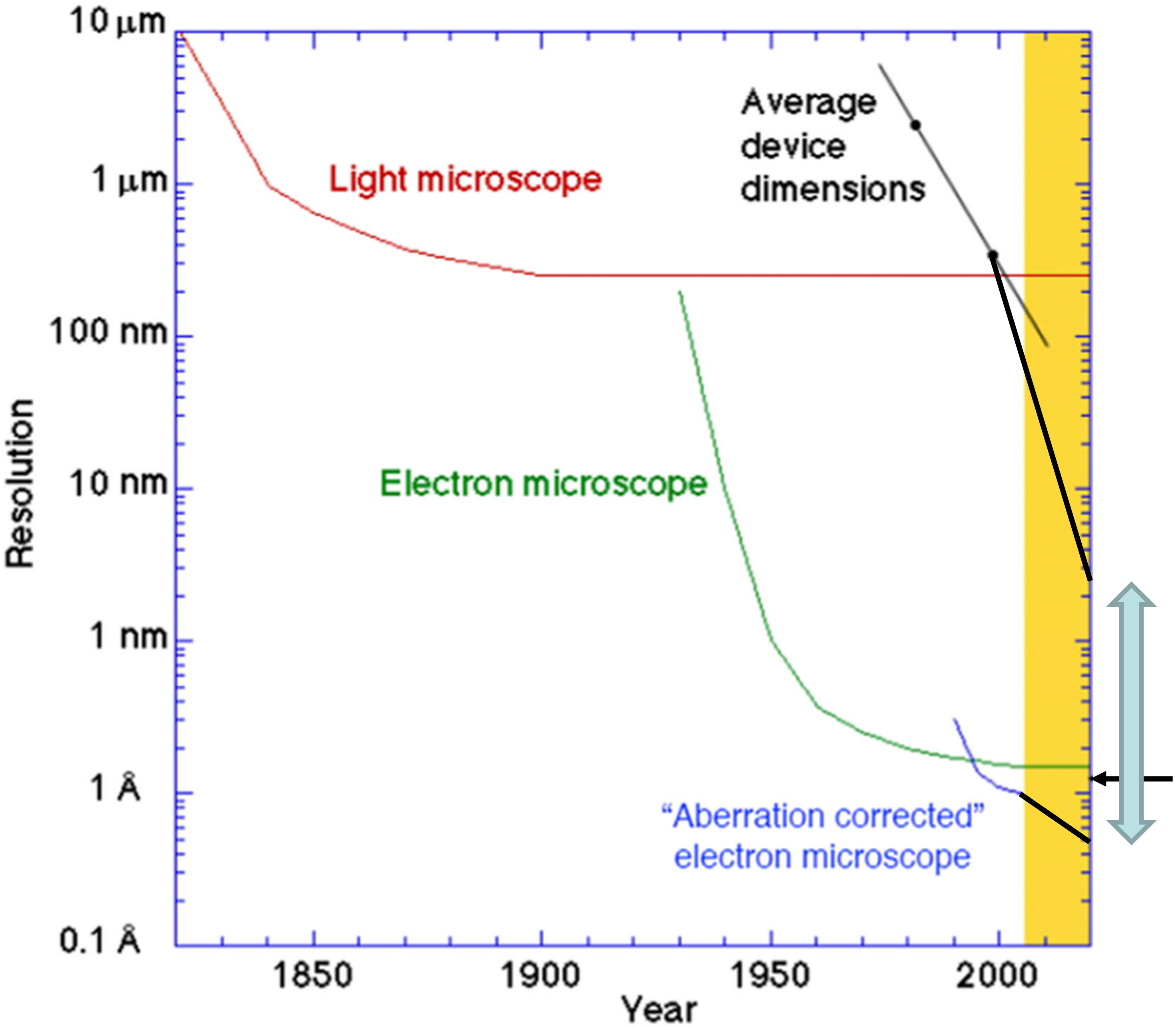


Luria and Anderson, first TEM image of a bacteriophage, 1942

Siemens TEM

E-Beam History

Electron microscope resolution



Light microscope: resolution limit ~300nm

Electron microscope: resolution limit should be ~ 0.001nm

TEM: resolution limit ~0.05nm "Aberration corrected" EM
Why such a huge difference?

Atomic spacing

E-Beam

Ultimate resolution

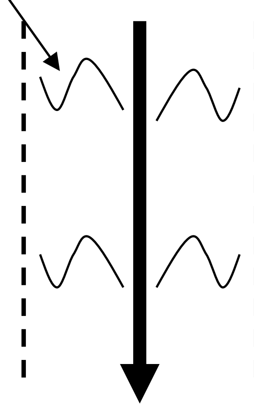
Secondary electron scattering

Types:

- Forward & Backward by primary beam
  ➔Proximity effects

1983 STEM (2-3 nm beam spot)
was used to write in 10 nm thick resist
with 300 keV electron beam
This gave **10 nm features**

Low energy electrons are needed for lithography, they break the bonds in the resist chains!



Solution Resist Processing

4 nm line width has been achieved through ultrasonic resist development. Use energy close to minimum exposure dose.

E-Beam

Electron scattering and proximity effect

Besides the system resolution and resist performance the **scattering of the electrons** in the resist is of crucial importance for the final resolution

Through what mechanism will the incoming electron beam lose its energy?

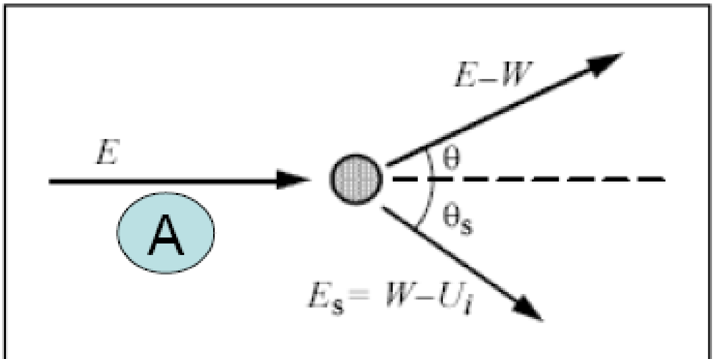
Electronic and Nuclear scattering

Which one is more important for lithography?
Electronic because of large cross section (ie high likely hood)

E-Beam

How do electrons interact with matter?

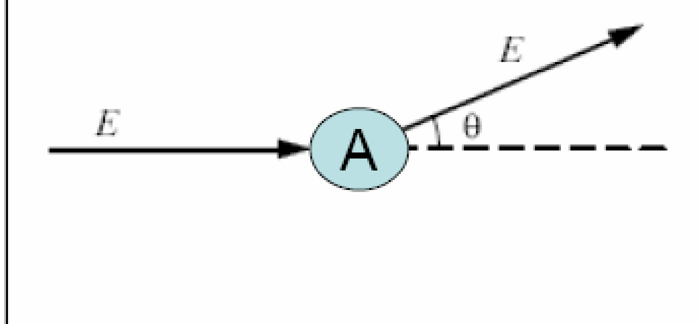
I Inelastic scattering on atomic orbital electrons ➔
Excitations + Ionization of Atoms
Collision Stopping Power



Inelastic scattering

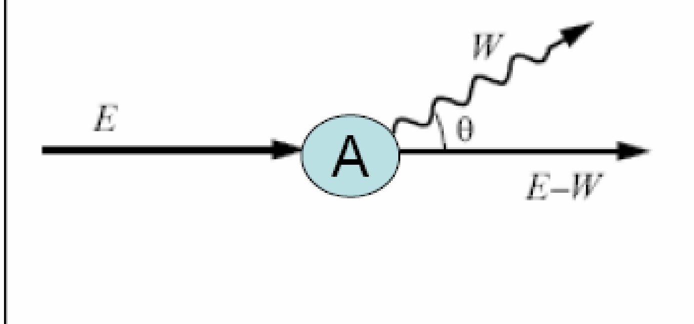
II Elastic scattering on atoms without significant energy exchange

Larger atoms (with a greater atomic number, Z) have a higher probability of producing an elastic collision because of their greater cross-sectional area



Elastic scattering

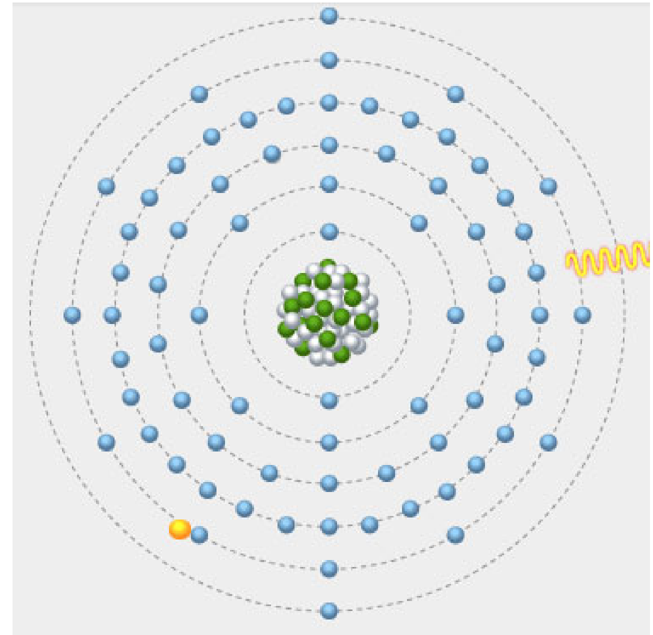
II Inelastic nuclear scattering. This results in radiation which is known as Bremsstrahlung
Radiative Stopping Power



Bremsstrahlung emission

E-Beam / X-rays

X-ray spectroscopy



When an electron hits a material X-rays are formed by 2 processes:

1) Bremsstrahlung

2) Characteristic X-rays/photons

Bremsstrahlung process

Caused by electrons being decelerated. Contains all energies from 0 to beam energy

Intensity given by Kramers law

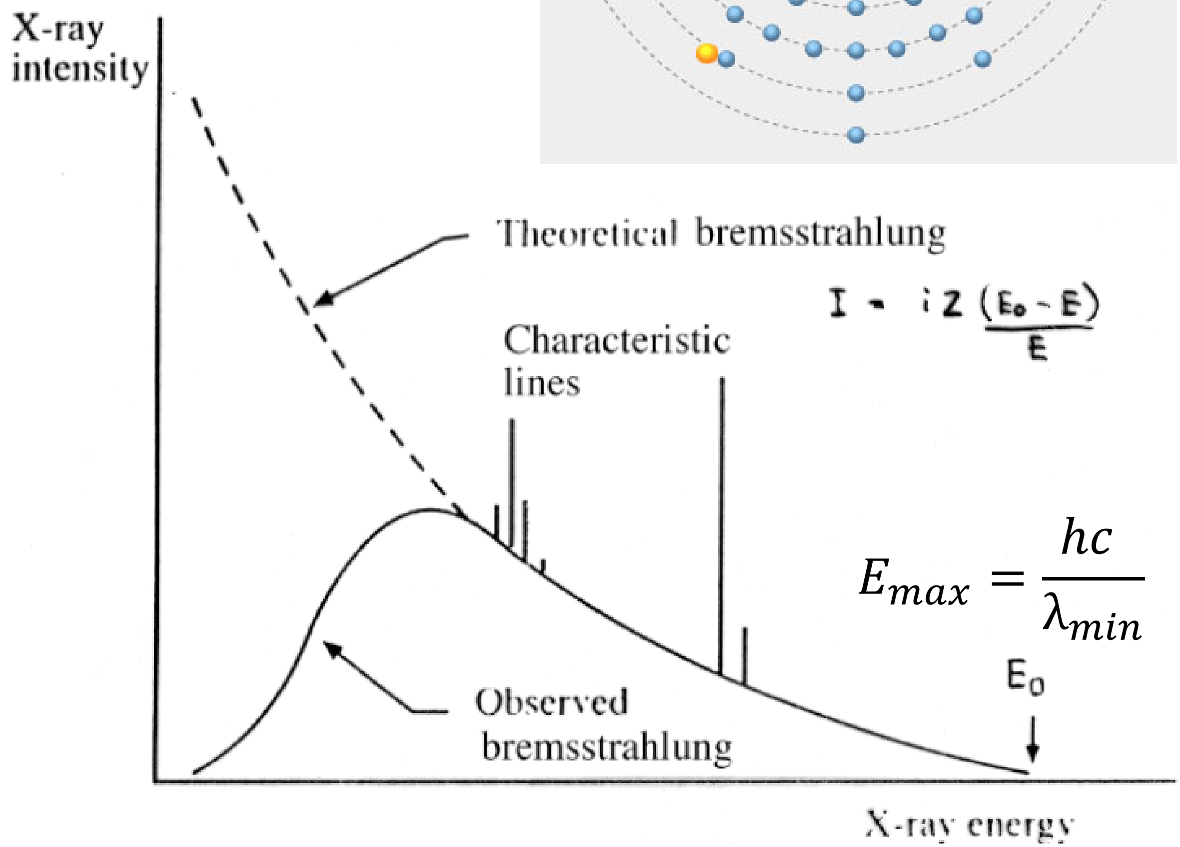
$$I = \frac{iZ(E_0 - E)}{E}$$

where

i = beam current

Z = average atomic number

E_0 = incident electron beam energy



Why does the observed X-ray intensity drop?

E-Beam / X-rays

X-ray spectroscopy (Characteristic X-rays)

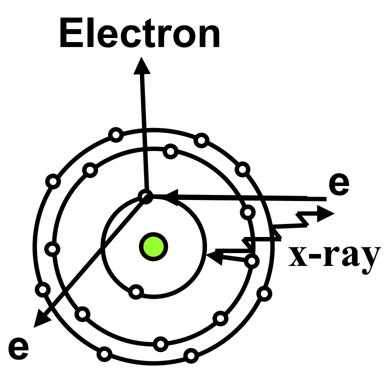
Primary electron removes electron from inner shell of target atom putting an ion in an excited state

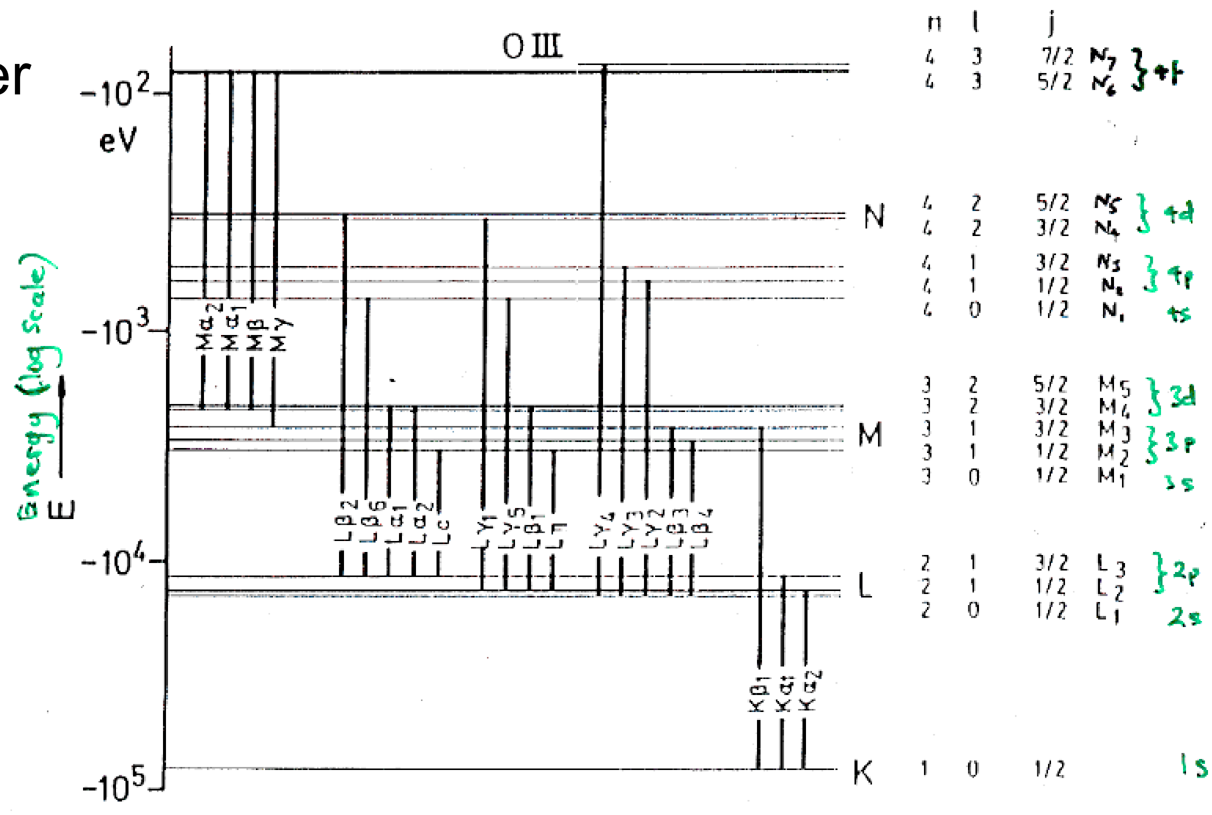
Ion loses energy by outer shell electron falling into vacancy

Excess energy emitted as either an X-ray or an Auger Electron

Probability of X-ray emission given by fluorescence yield, ω_k, ω_l, ω_m

ω small for low Z





K, L and M characteristic lines for Au

E-Beam / X-rays

Energy dispersive X-ray spectroscopy (EDX)

Typical limits of detection 0.1%