2009 spring

Microstructural Characterization of Materials

04. 29. 2009

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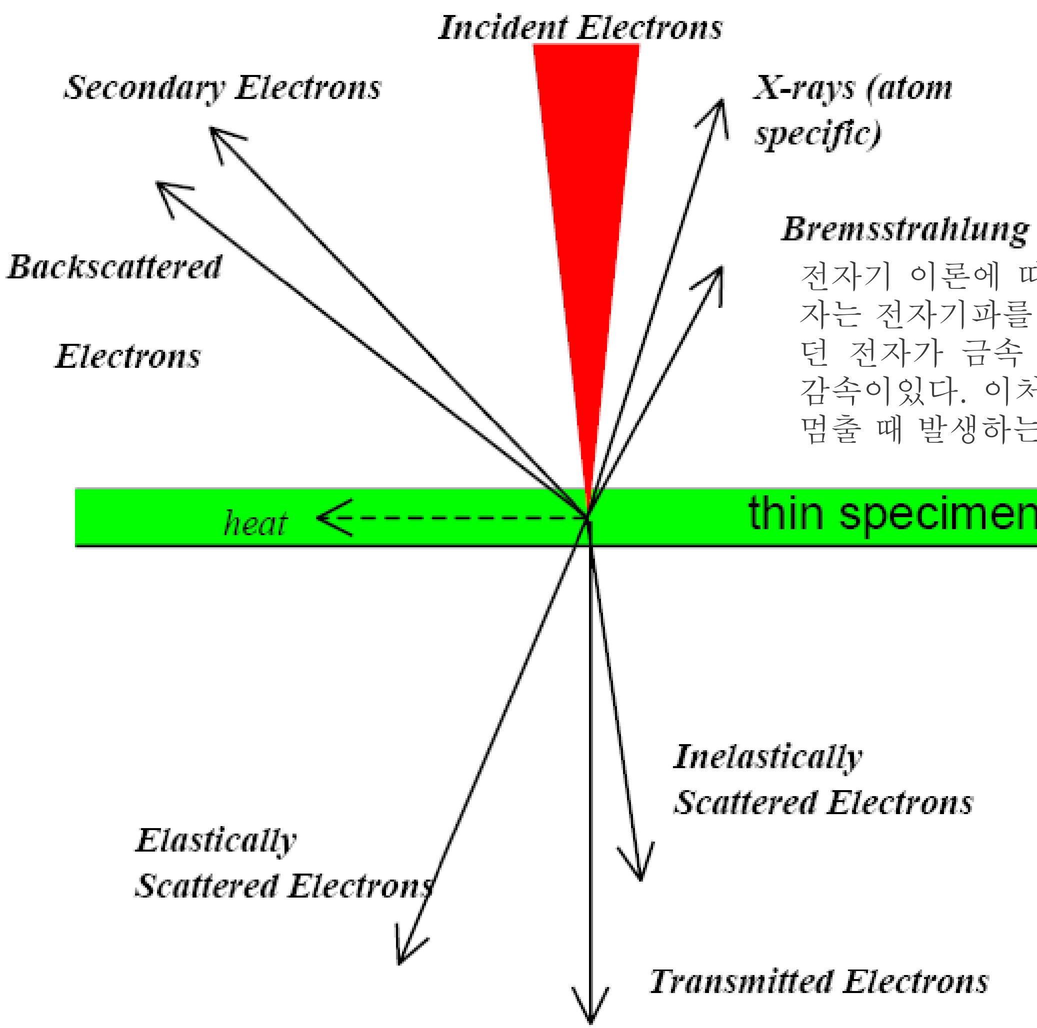
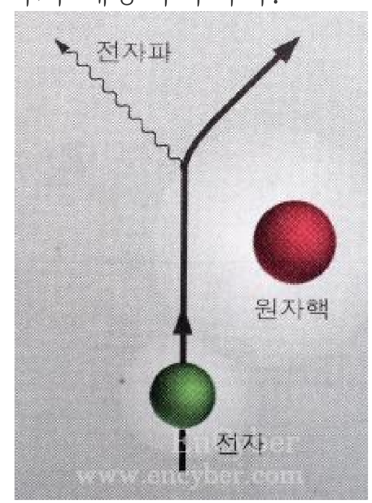
Interaction of high energy (~kV) electrons with (solid) materials-II

Interaction with a thin specimen (TEM & STEM)



제동복사 [制動輻射]

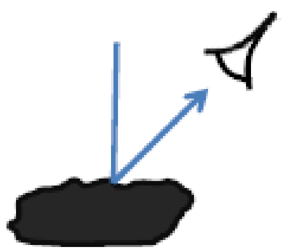
전자기 이론에 따르면 가속이나 감속되는 전자는 전자기파를 발생 시킨다. 빠르게 움직이던 전자가 금속 등에 부딛쳐 갑자기 멈추면 감속이있다. 이처럼 빠르게 움직이던 전자가 멈출 때 발생하는 복사가 제동복사이다.



reminder

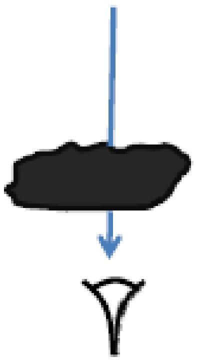
2 different approaches:

Backscattered and secondary electrons



SEM

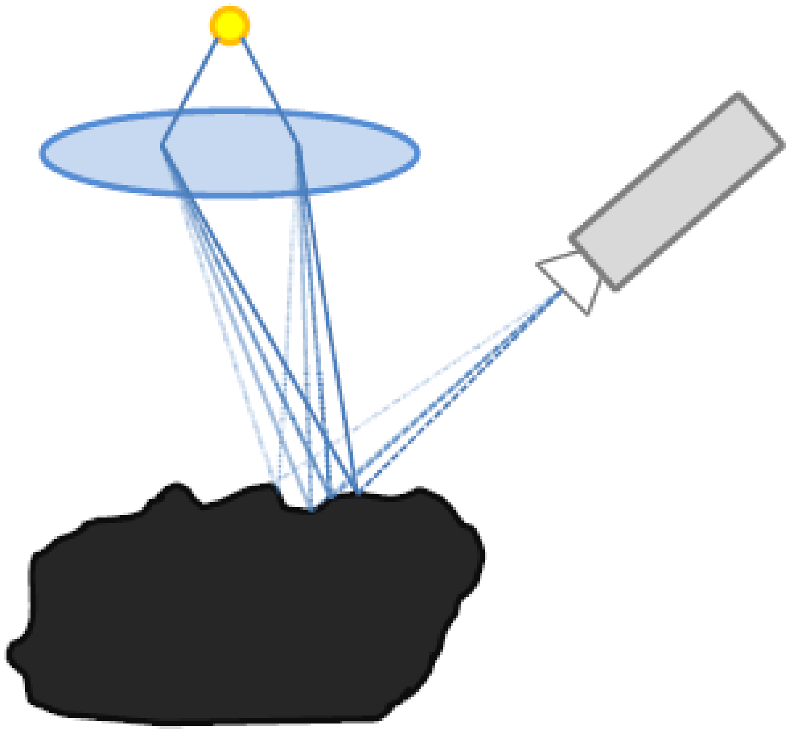
Transmitted electrons



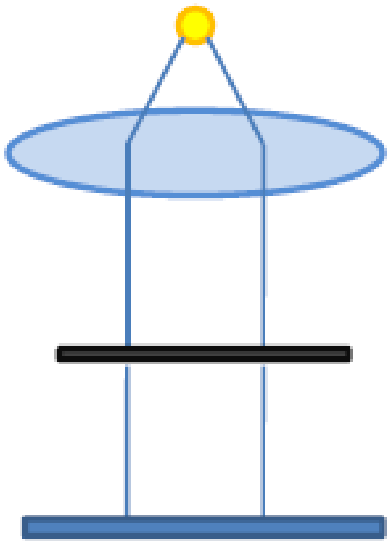
TEM

reminder

SEM: scans with a focused point



TEM: illumantes whole sample



TEM Construction

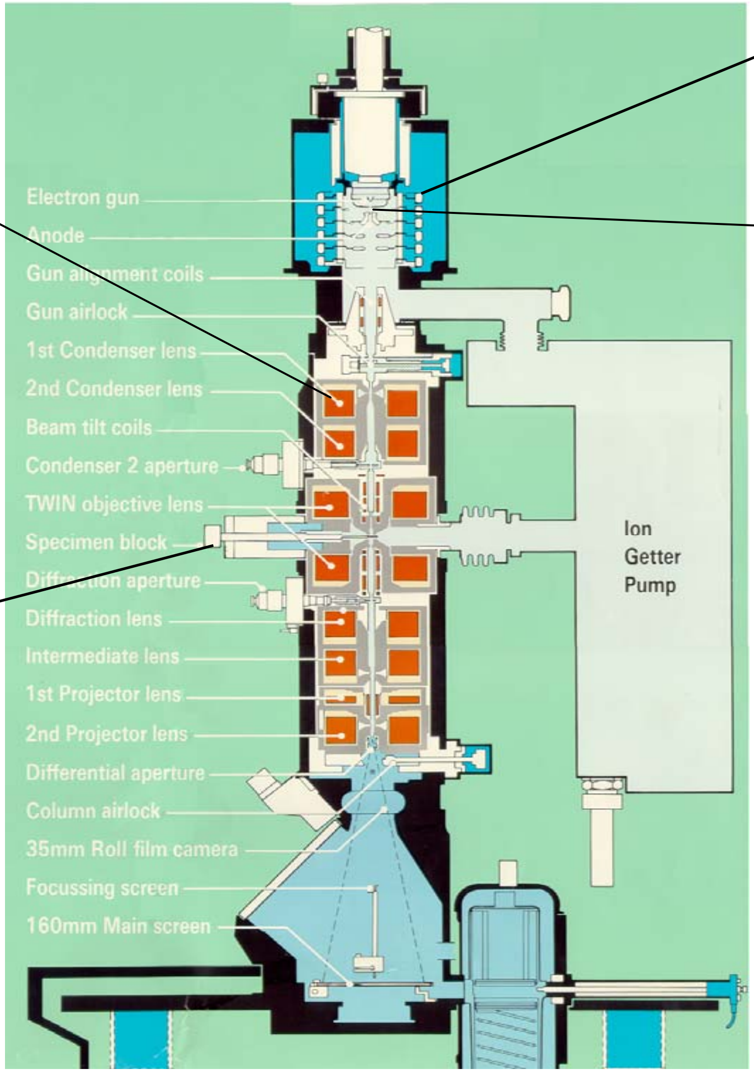
Cross-sectional view of CM12

Electro-magnetic lens

Plus many more Electromagnetic lens… Apertures...

Sample loadlock

Energetic electron to visible light conversion



High voltage insulation

Electron Source

Image recording system

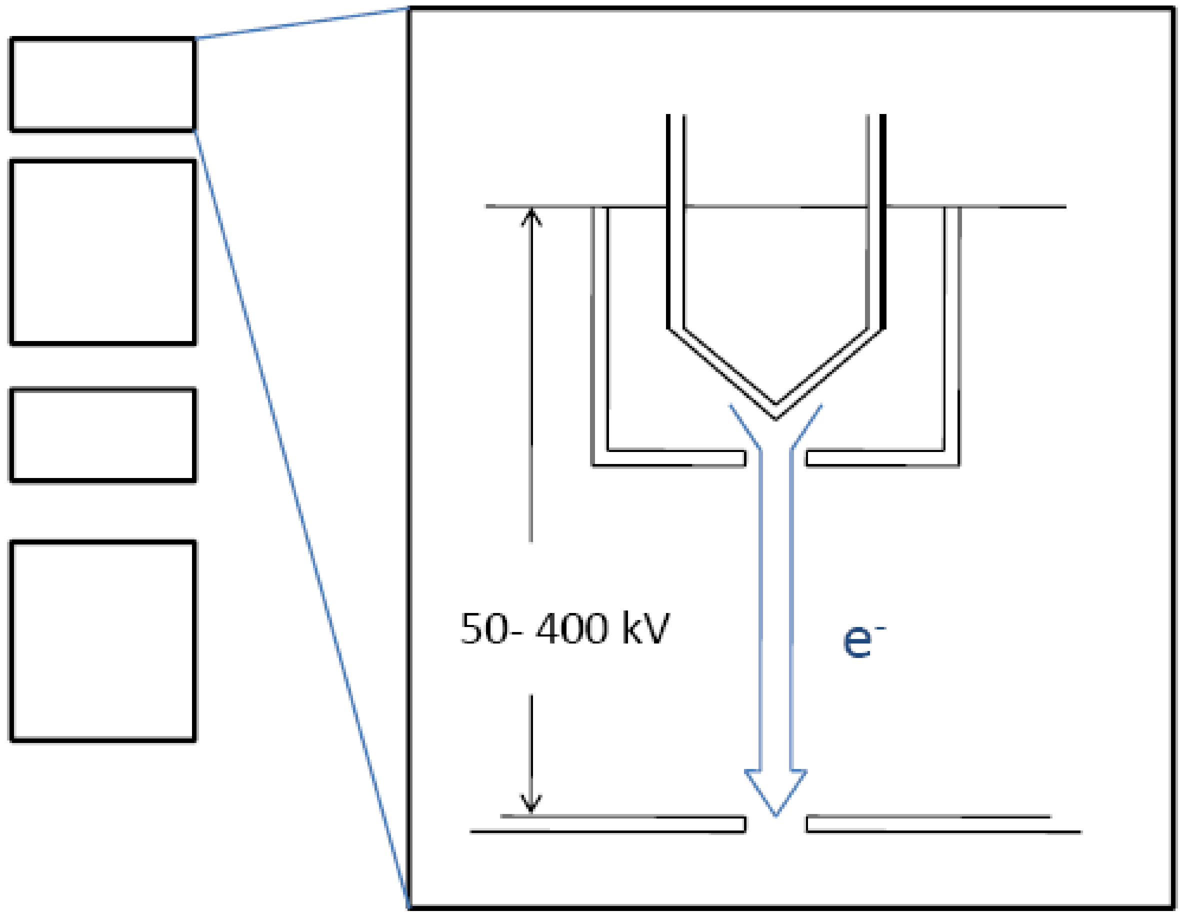
Functional Principle

Electron gun

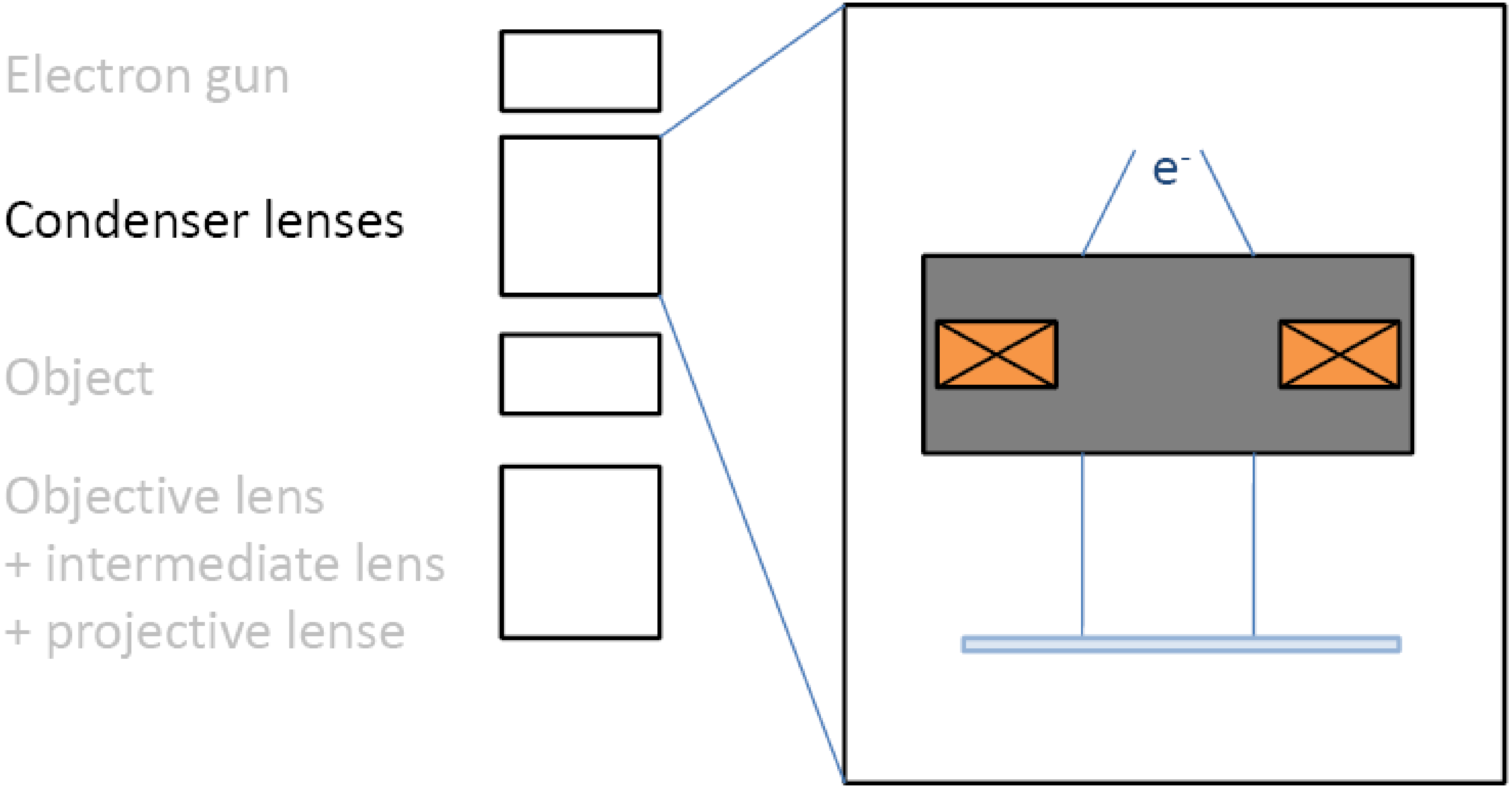
Condenser lenses

Object

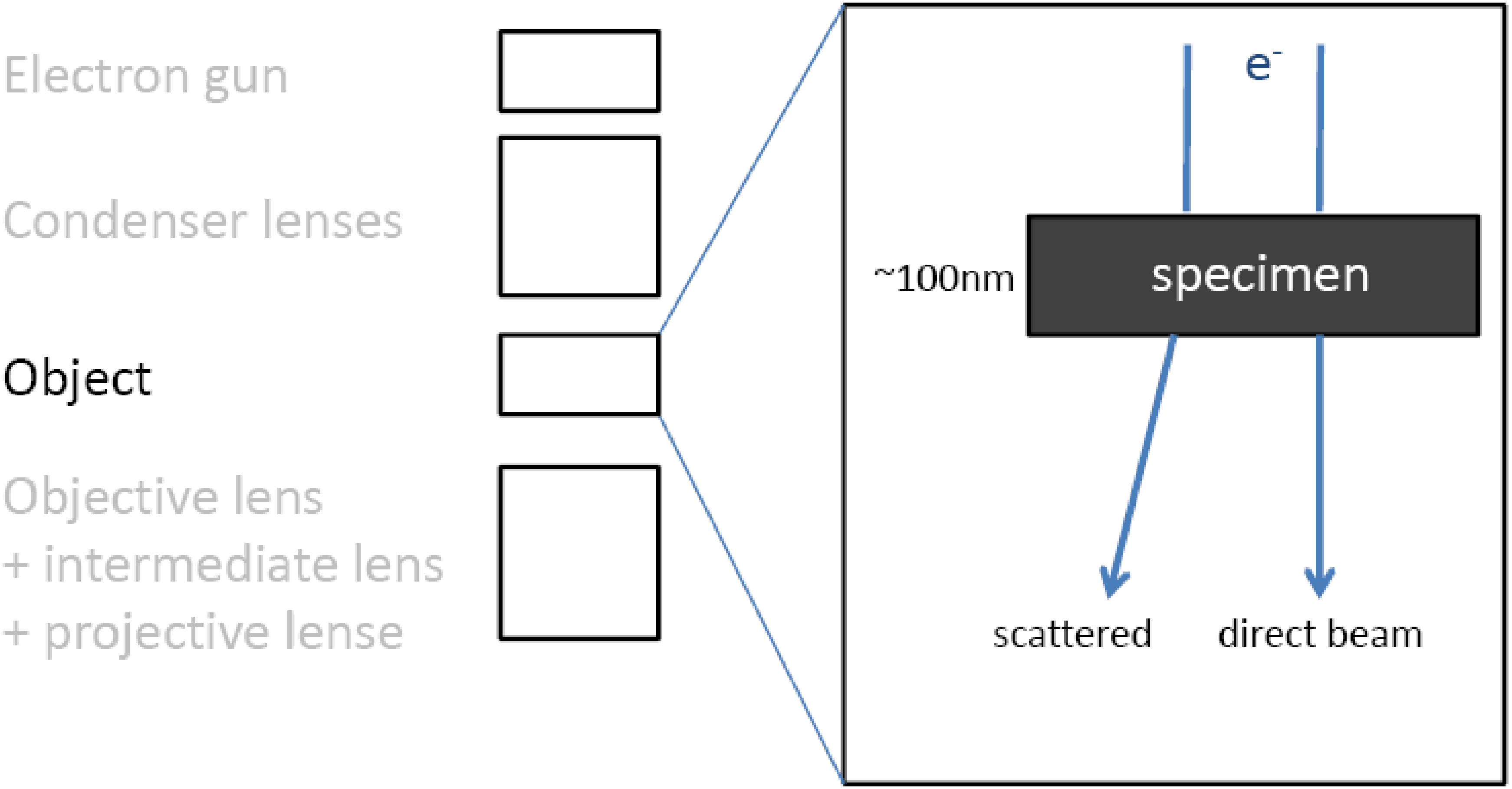
Objective lens
+ intermediate lens
+ projective lense



Functional Principle



Functional Principle



Functional Principle

Electron gun

Condenser lenses

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Objective lens
+ intermediate lens
+ projective lense

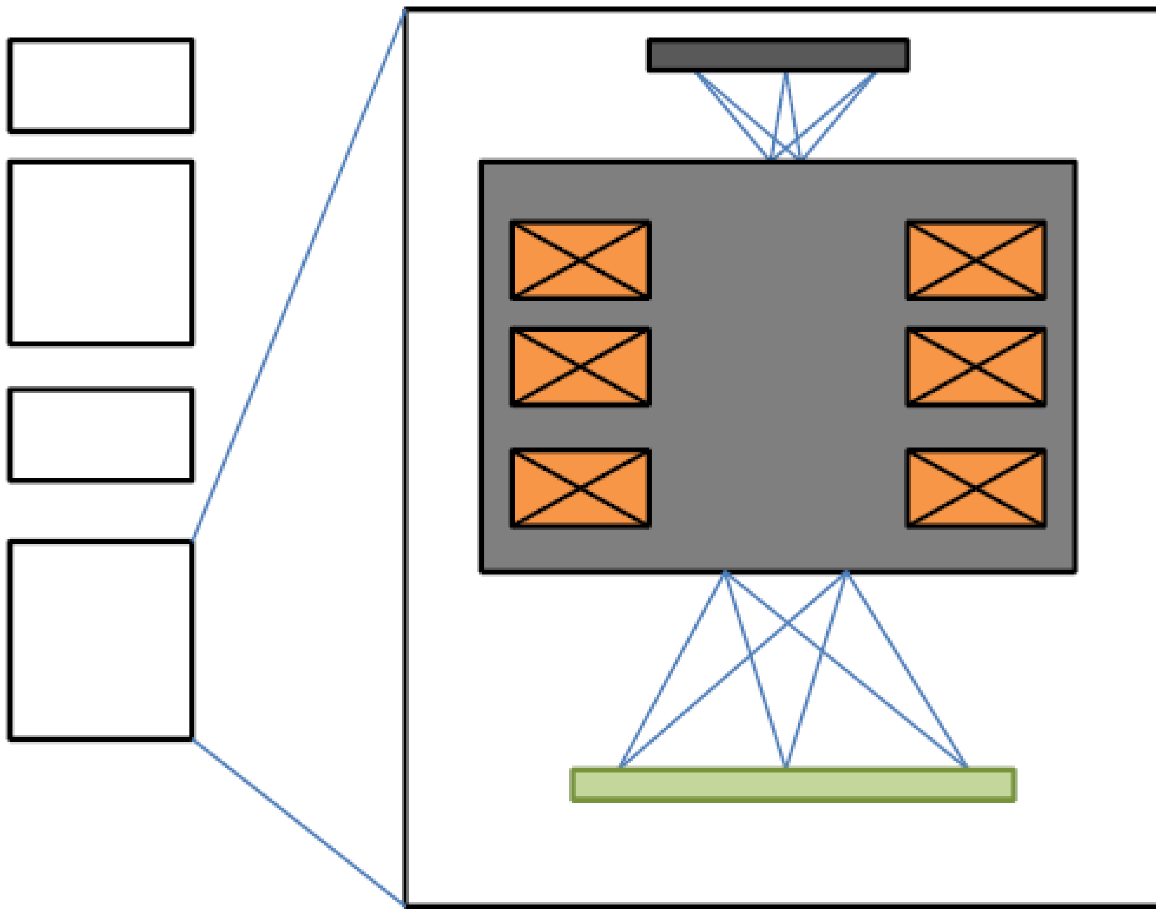
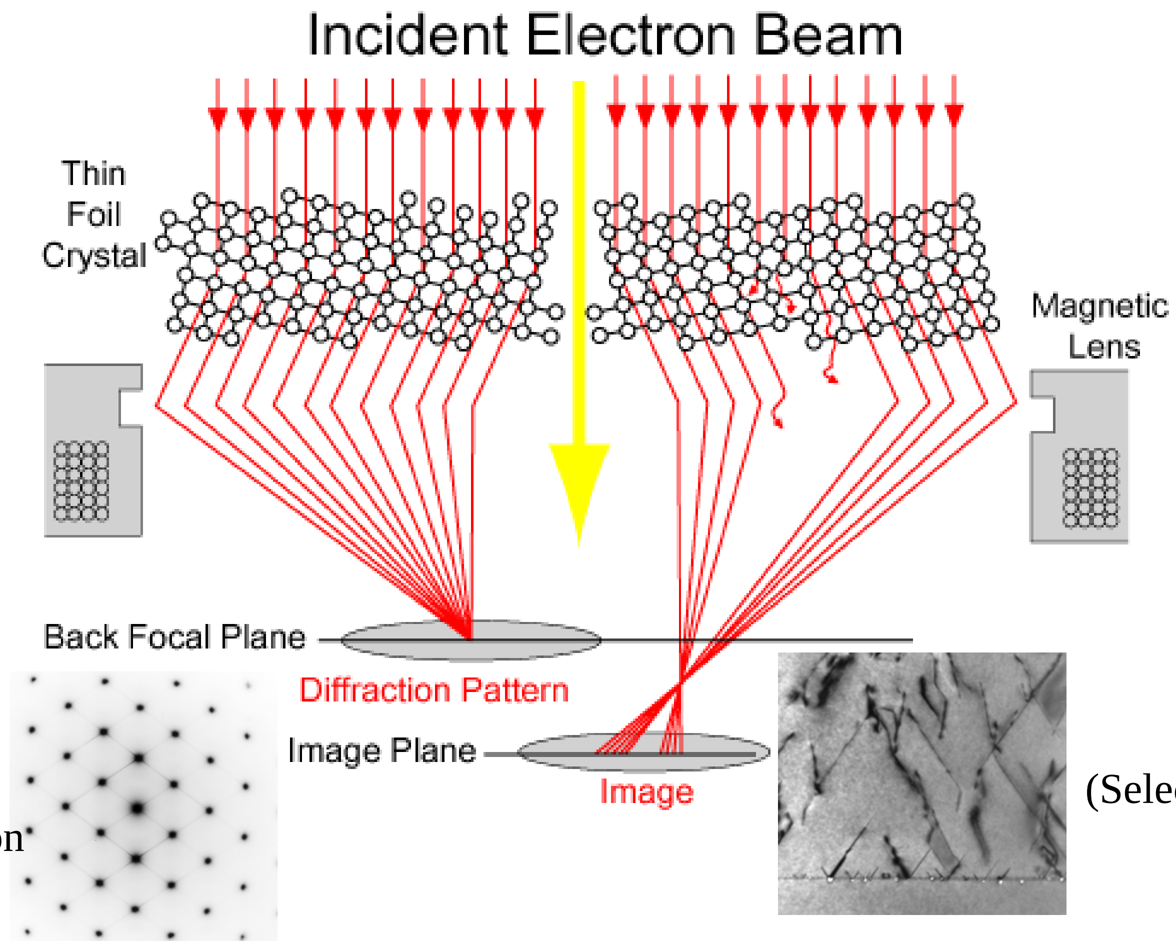


Image and Diffraction

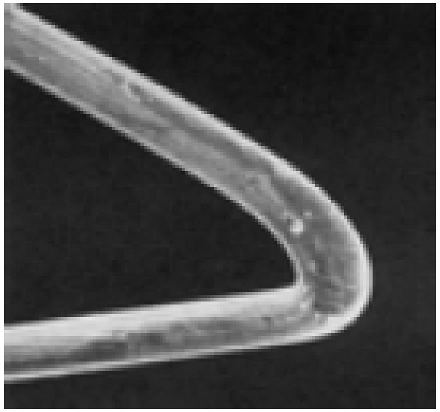


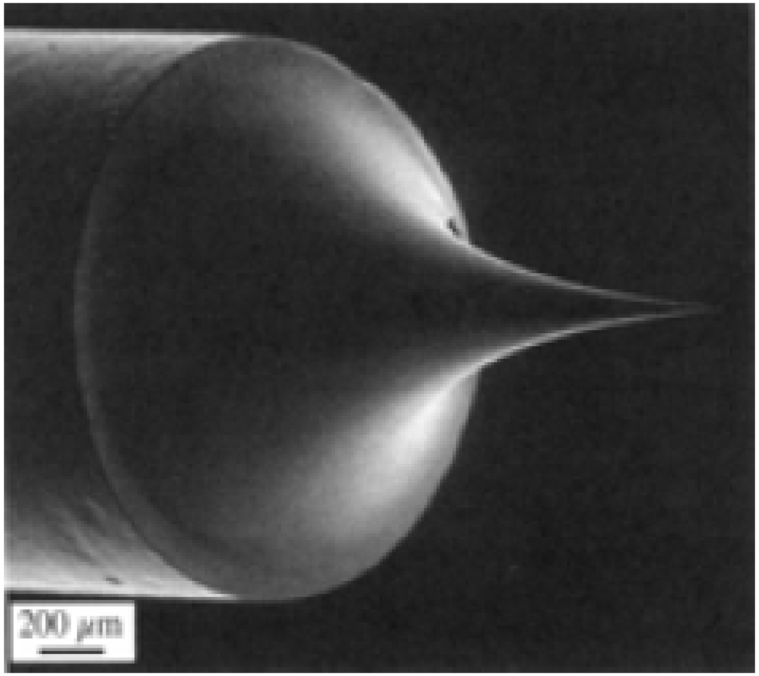
Diffraction Pattern
(Fourier transformation
of periodic object)

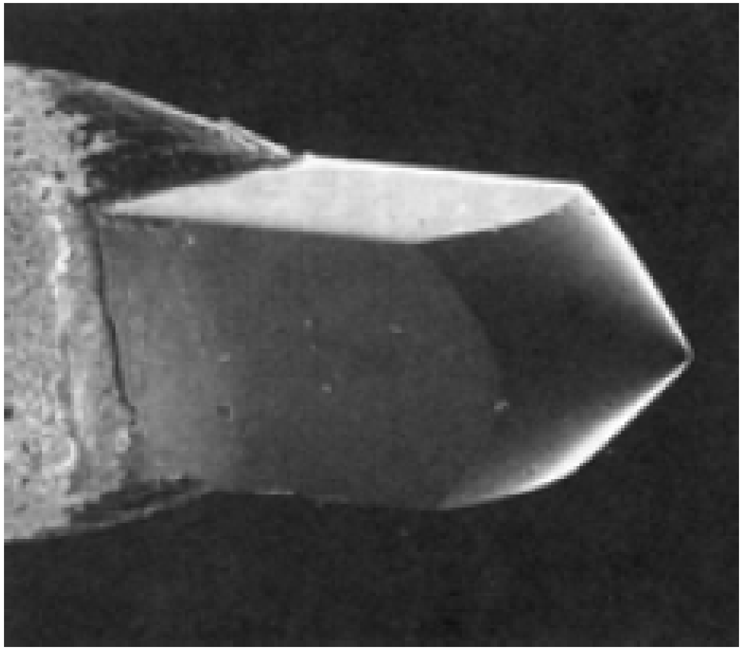
Image
(Selected diffraction
planes)

- **Diffraction occurs from the planes nearly parallel to the beam direction**

$$\lambda = 2d \sin\theta_B, \text{ where } \theta_B < 0.5 \text{ degree}$$

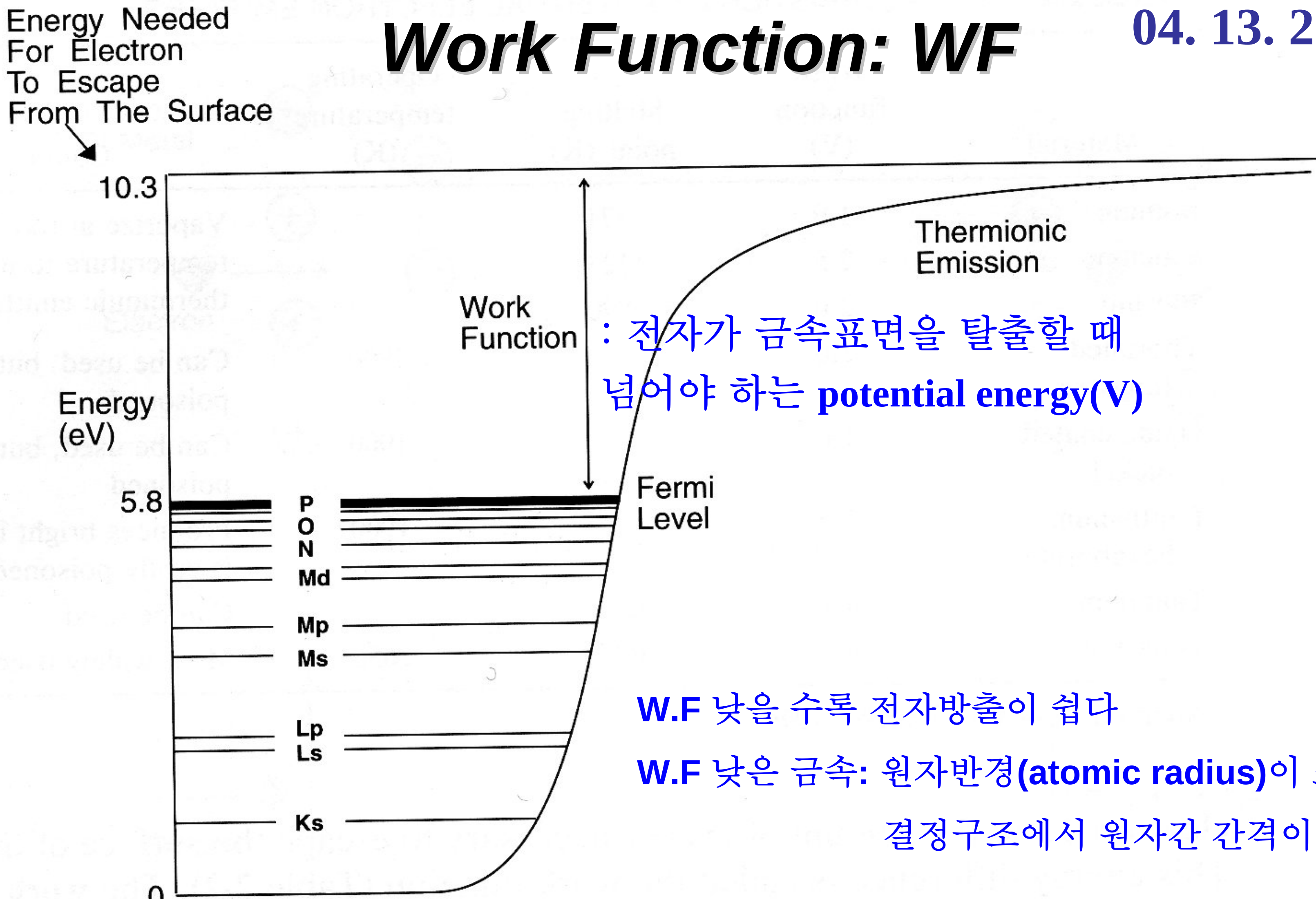



200 μm



Work Function: WF

04. 13. 2009



: 전자가 금속표면을 탈출할 때 넘어야 하는 **potential energy(V)**

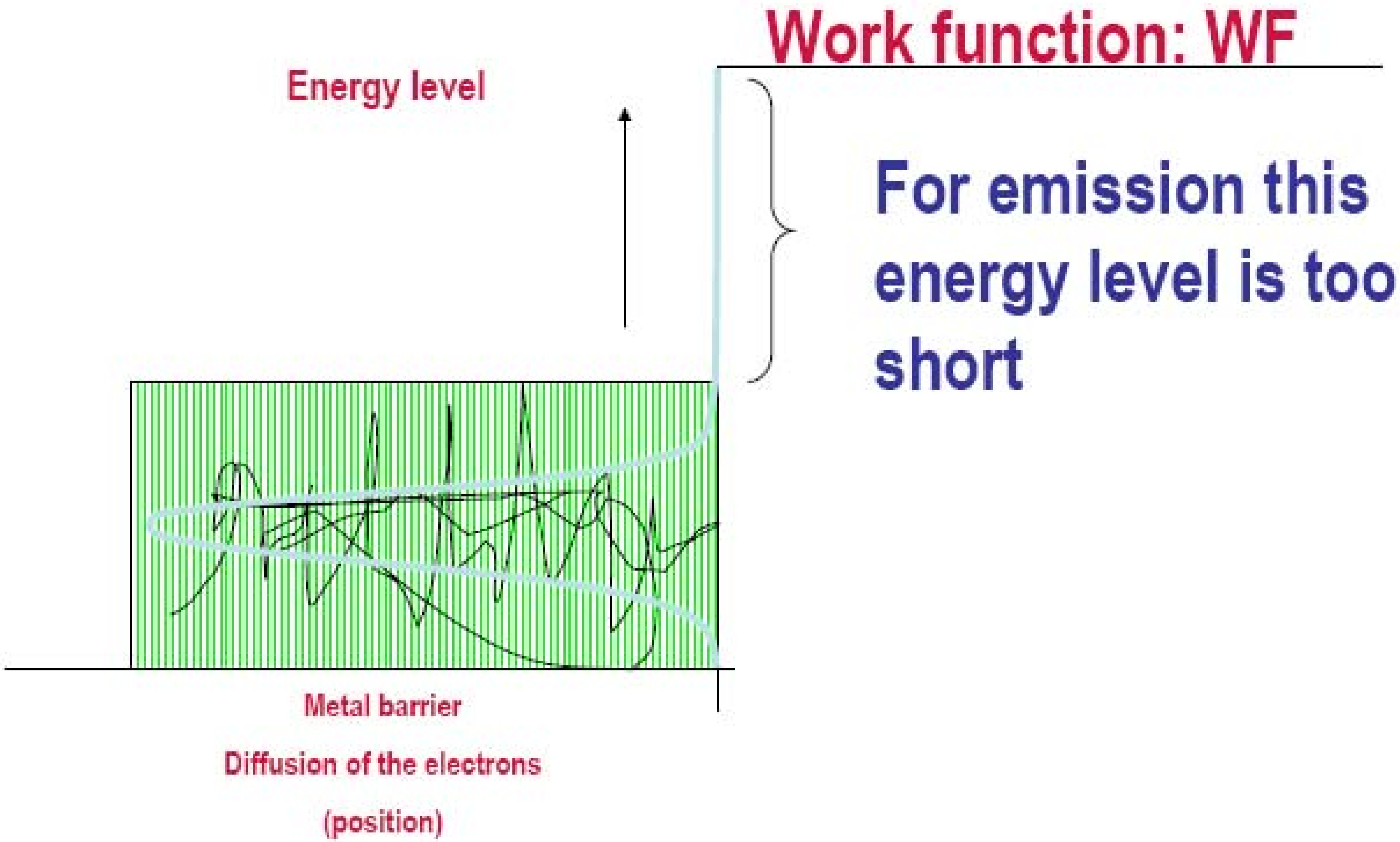
W.F 낮을 수록 전자방출이 쉽다

W.F 낮은 금속: 원자반경**(atomic radius)**이 크다

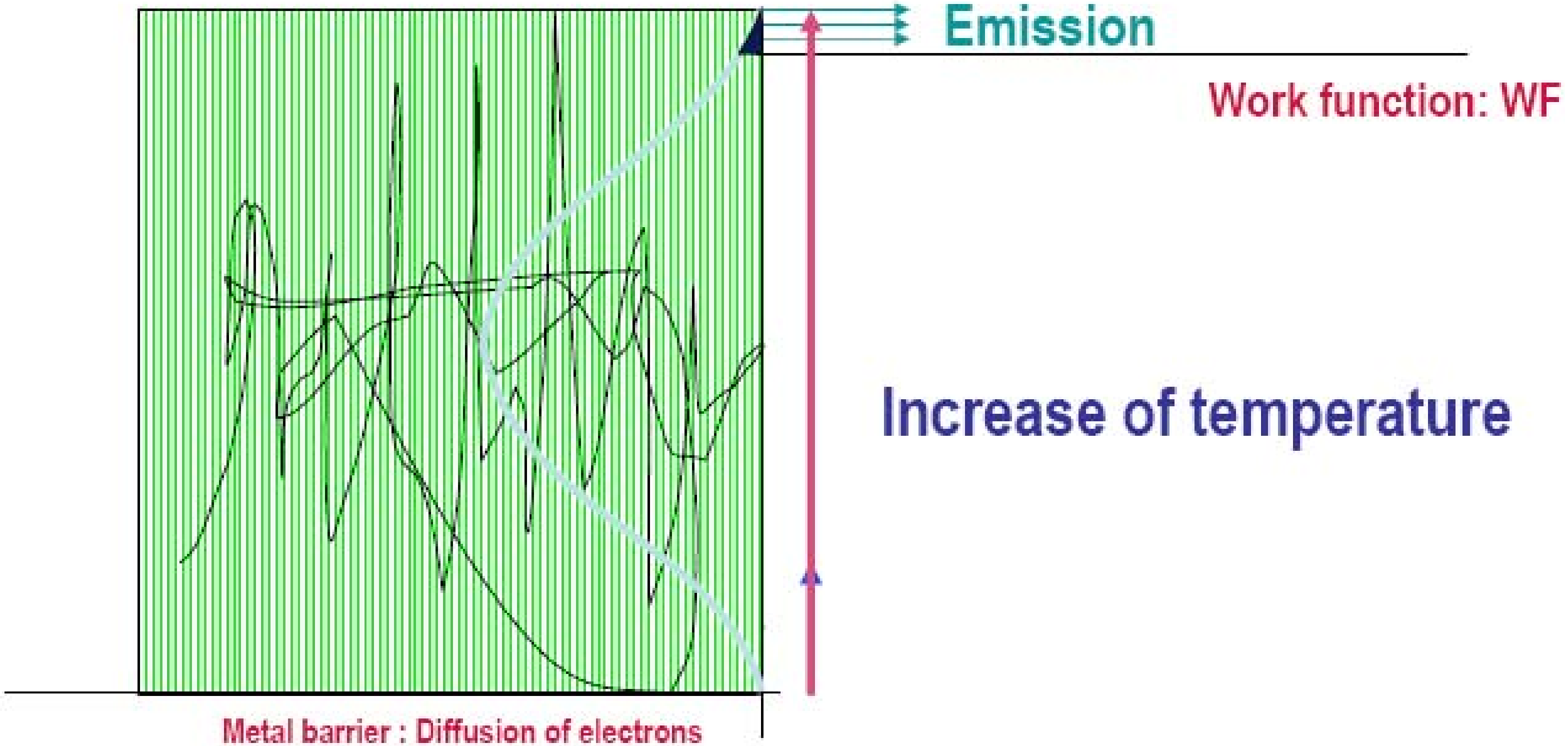
결정구조에서 원자간 간격이 크다

Figure 2-3 Thermionic emission curve of tungsten. Diagram of the energy of the orbital electrons of tungsten showing that the work potential is the difference between the energy necessary for the electrons to escape from the surface of the metal and the energy of the highest-orbital electrons.

How to get electron emission?



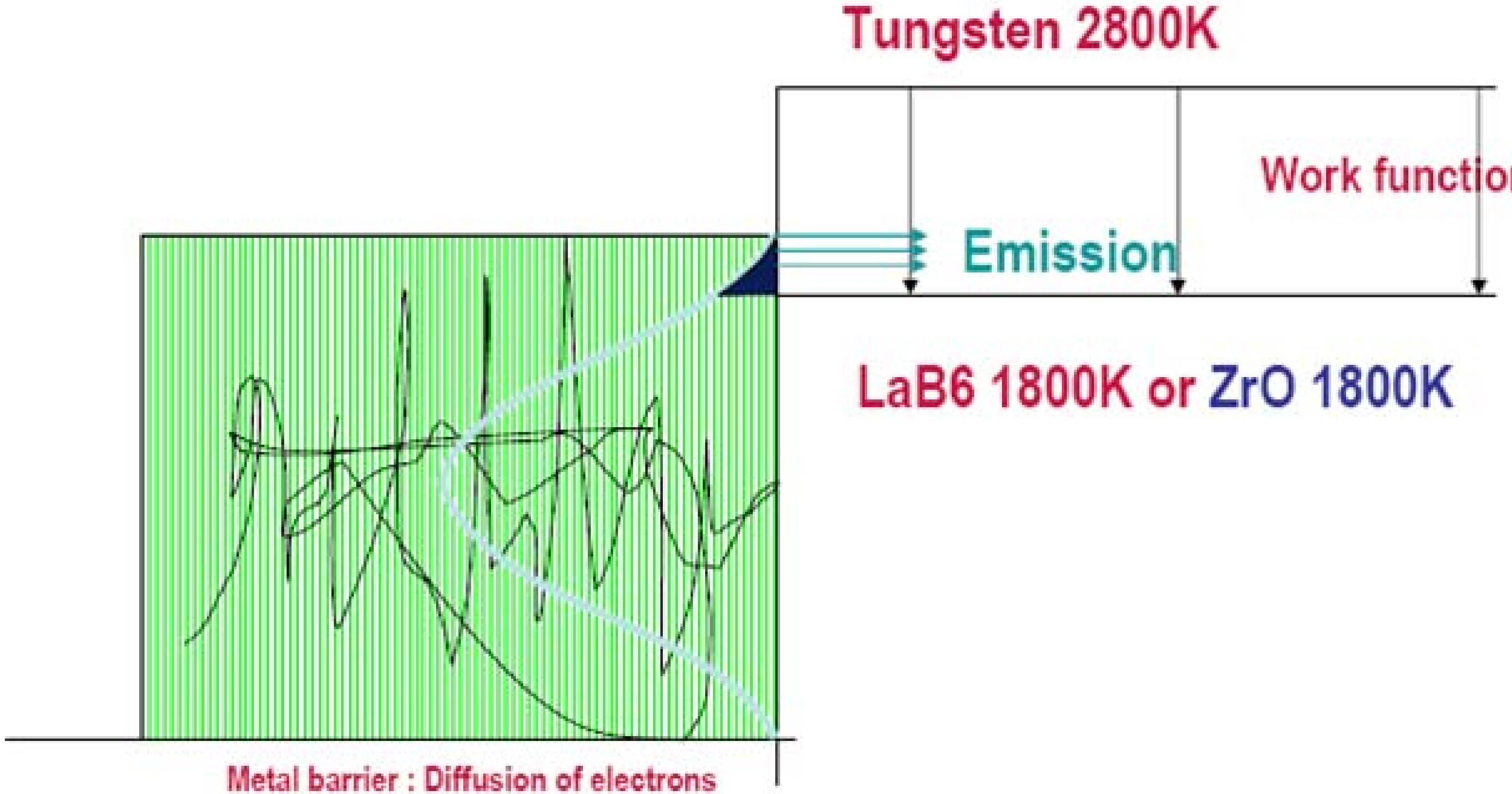
Thermal Emission



Electrons need to have more energy than the *work function* (WF) to leave the emitter.

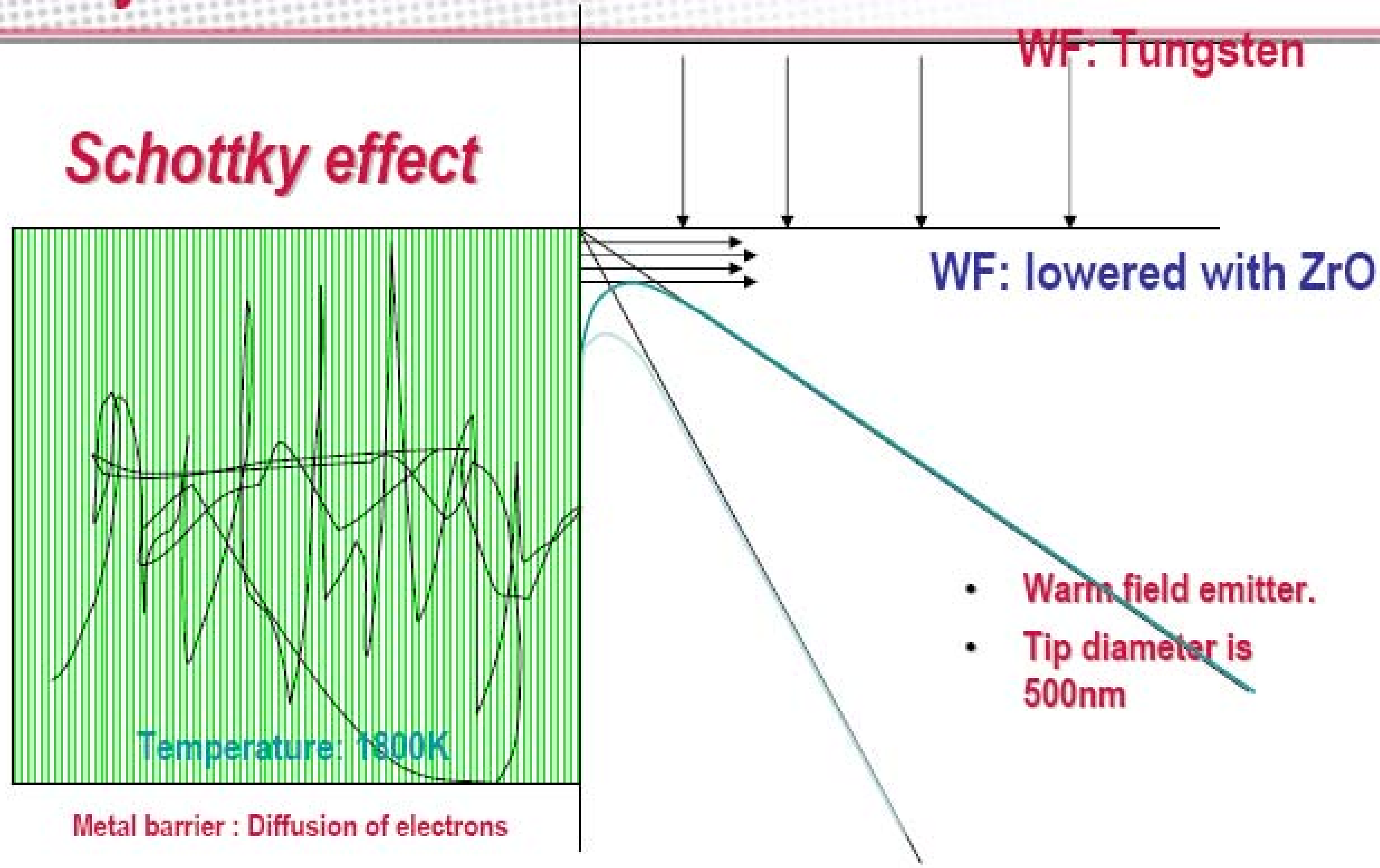
Their energy depends on the temperature, so *heating* can be used to cause emission (*thermionic* emitter like W or LaB6).

A lower work function



The WF depends on the material, so choosing a material with a low WF helps emisison (LaB6 or ZrO layer on FEG emitter). It also depends on the *crystal orientation* (FEG).

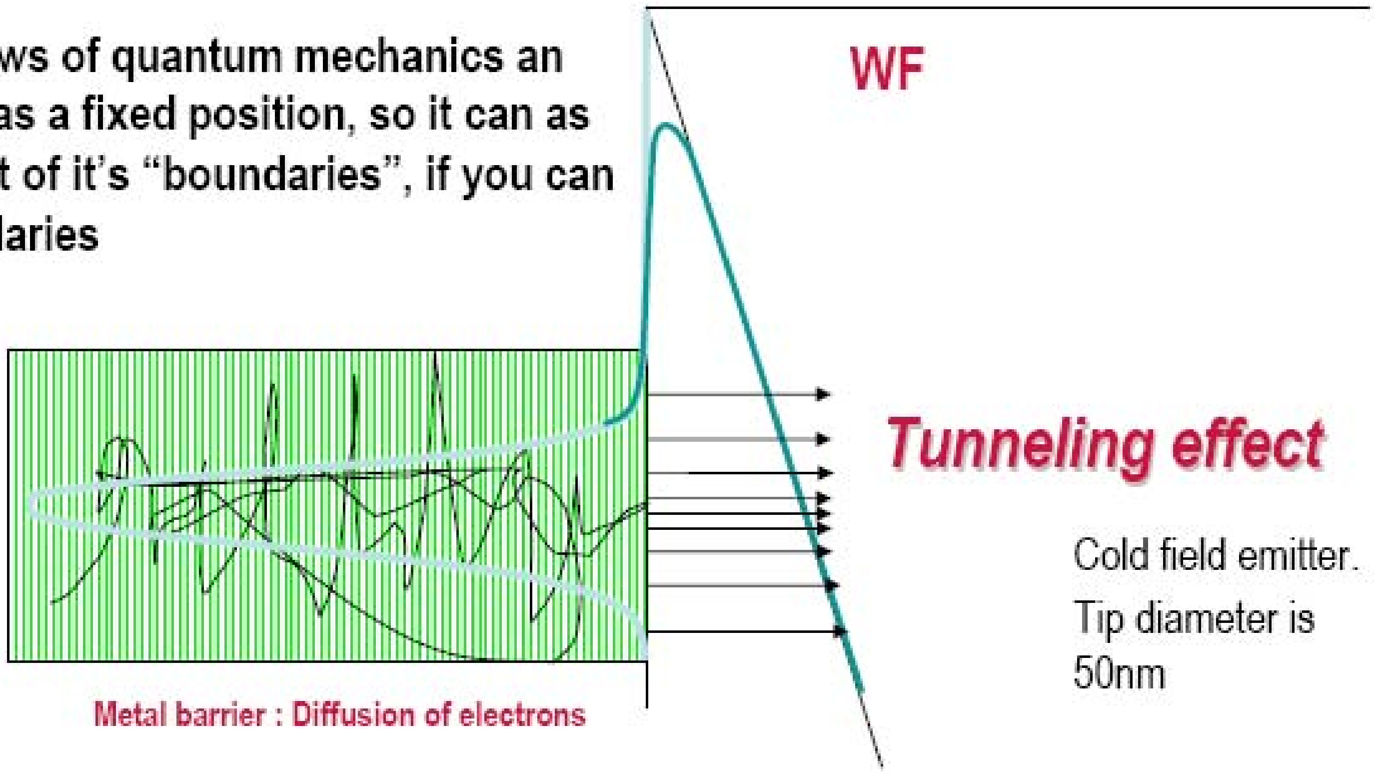
Schottky emitter



The *Schottky effect* is that the WF becomes lower when a strong electric field is applied on the emitting surface(used in SFEG).

Tunneling effect

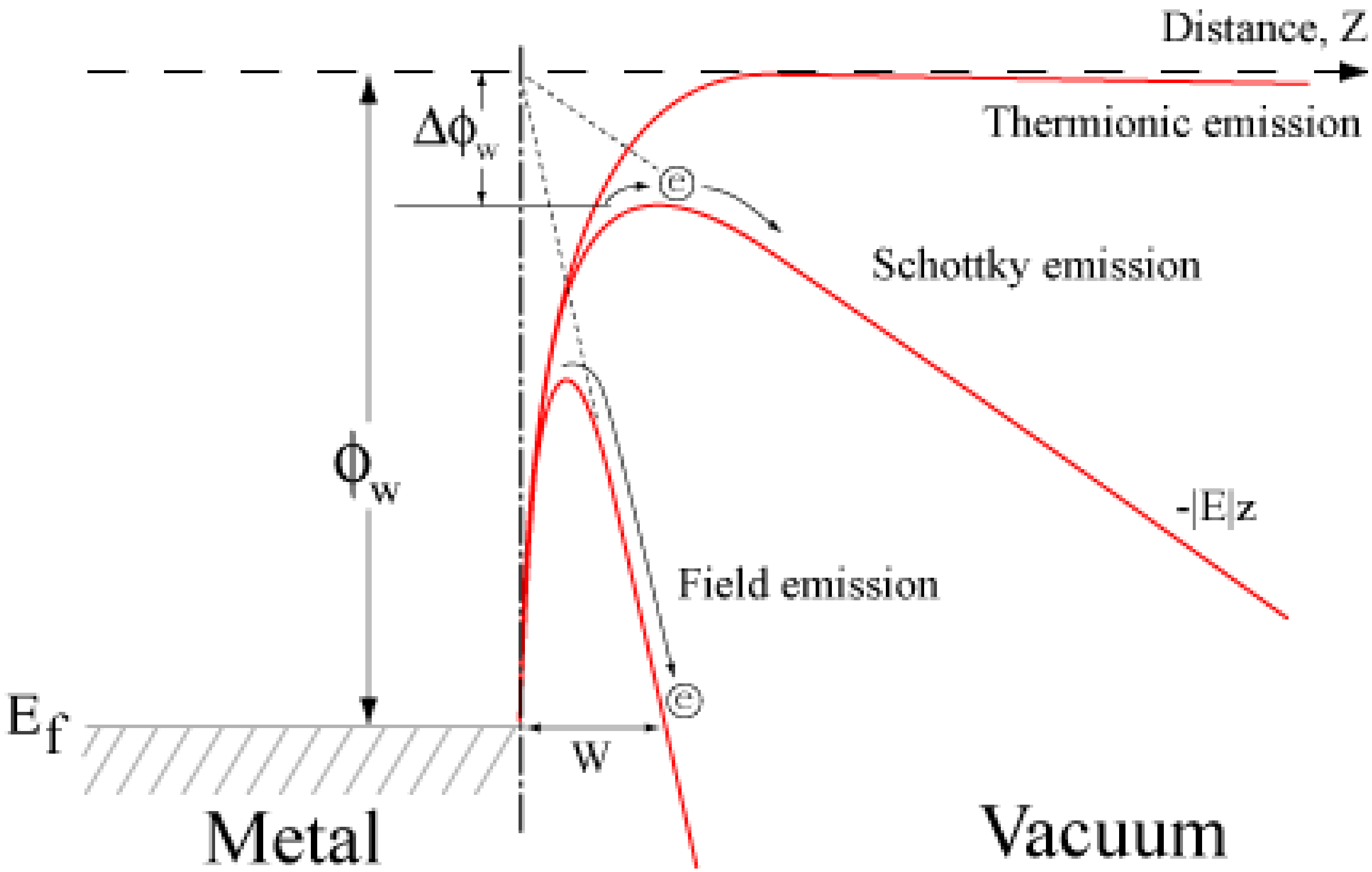
According the laws of quantum mechanics an electron never has a fixed position, so it can as well be found out of it's "boundaries", if you can talk about boundaries



Cold field emitter.
Tip diameter is 50nm

Field emission occurs at even higher electric fields. In this case the electrons tunnel through the now very thin barrier(used in CFEG).

Field emission of electron



Schematic view

W 원자의 가장 높은 궤도의 전자들은 실온에서 **energy barrier**를 넘기 힘들다.

그러나 금속이 강한 전기장**(electric field)** 이 놓이면 궤도전자들은 **potential barrier energy**를 통해 **tunneling**해서 금속 표면에서 방출된다.

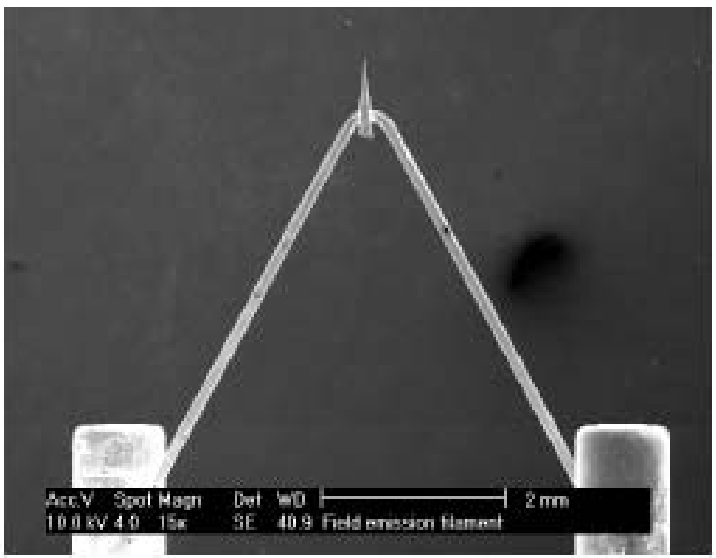
Cold field Emission

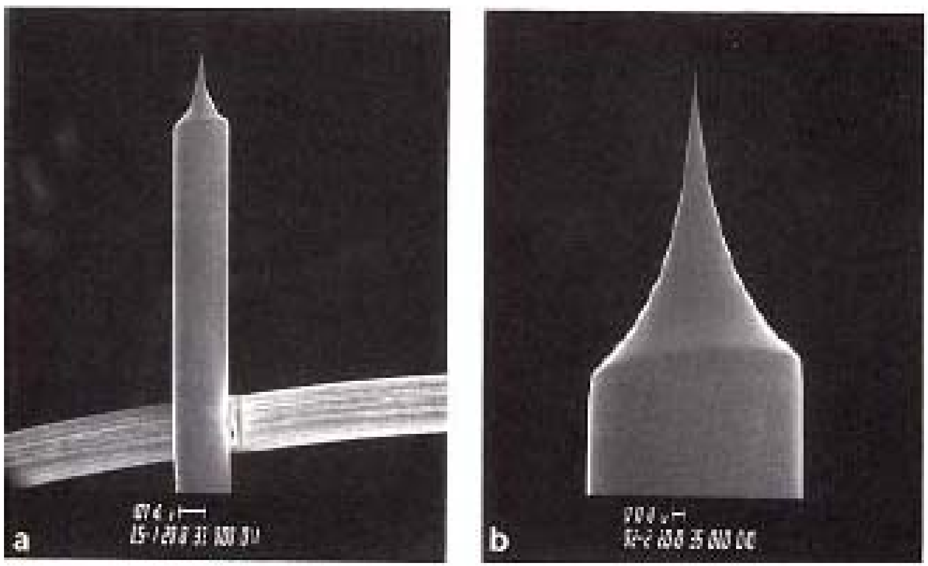
advantages: small spot size (1-2nm) ➡ high resolution

low ΔE ➡ improving of low volt. Operation.

Tip 에 high electric field 를 주어 electron 을 방출

W<100> & W<310> single crystal
10e-10 torr 이상의 고진공
Flashing (burn out) 필요:
고진공 상에서도 tip 의 표면에 기체원자들이
흡착될 수 있어 emission 을 적게 만들므로 tip 을 고온으로 가열하여 흡착물을 제거
Flashing 후 안정화 까지 기다려야 하며, 또한 tip 수명 단축





Thermal Field Emission

advantages: No flashing, brightness is similar to cold FE

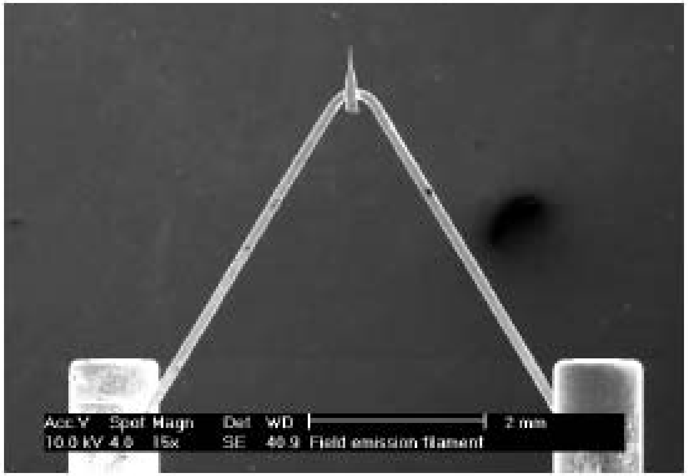
W<100> single crystal

Continuous Heating (1300 ~ 2000K)

No Flashing

Lower vacuum 10e-9 torr

단 점 : energy spread 가 높음 (chromatic abberation 증가)
(larger ΔE)



Schottky Field Emission

1800 K

ZrO2 를 W 의 <100> 면에 코팅하여,

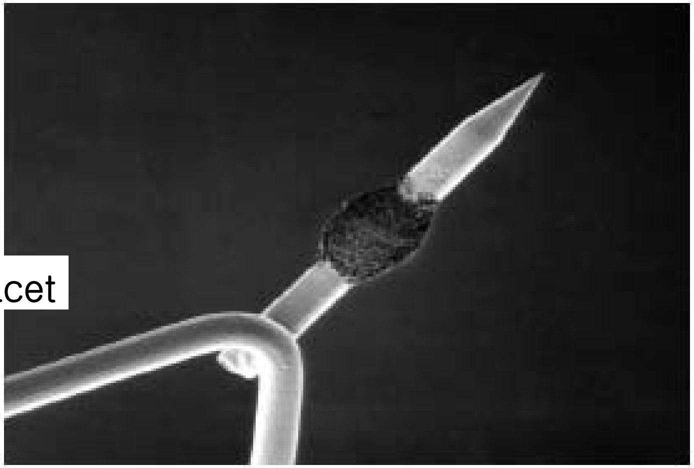
일함수를 4.5 Ev 에서 2.8 Ev 로 낮추기 때문에,

즉 schottky barrier 가 낮아지는 효과를 이용

장 점 :

good emission stability : flat emitting area on <100> facet

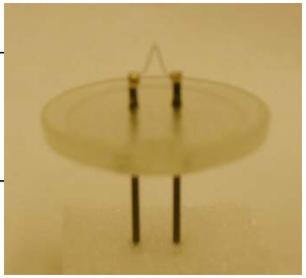
good energy spread



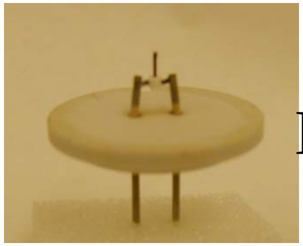
Electron sources

Table 2.1. Some features of electron sources

Emission	Thermionic	Thermionic	Schottky	Field emission
Material	W	LaB_6	ZrO/W	W
Work function (eV)	4.5	2.7	2.5	4.5
Working temperature (K)	2800	1400-2000	1400-1600	300
Emission current density (A/cm^2)	1	10^2	10^3	10^5
Gun brightness ($A/(cm^2 \cdot sr)$)	10^5	10^6	10^8	10^8
Crossover diameter (μm)	30	10	1	0.01
Energy width (eV)	1-2	0.5-2.0	0.3-1.0	0.2-0.4
Life (h)	~50	~1000	~25,000	~1000
Vacuum requirements (Pa)	10^{-2}-10^{-3}	10^{-3}-10^{-4}	10^{-7}-10^{-8}	10^{-8}-10^{-9}



W



LaB_6

FEG

Basic electron optics

- Electrons and ions are charged particles, they can be accelerated in a **E** field.
- The trajectory of an accelerated charged particle can be deflected by **E** and/or **B** field.
- According to *de Broglie*, the accelerated (high-energy) particles also behave like waves.

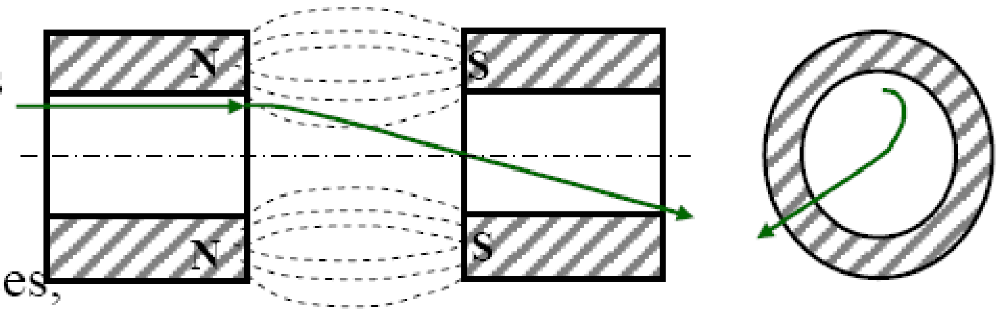
Lenses

- Provide means to (1) (de)focus the electron beam on the specimen, (2) to focus the image, (3) to change the magnification, and (4) to switch between image and diffraction

Round Lenses

Magnetic lenses

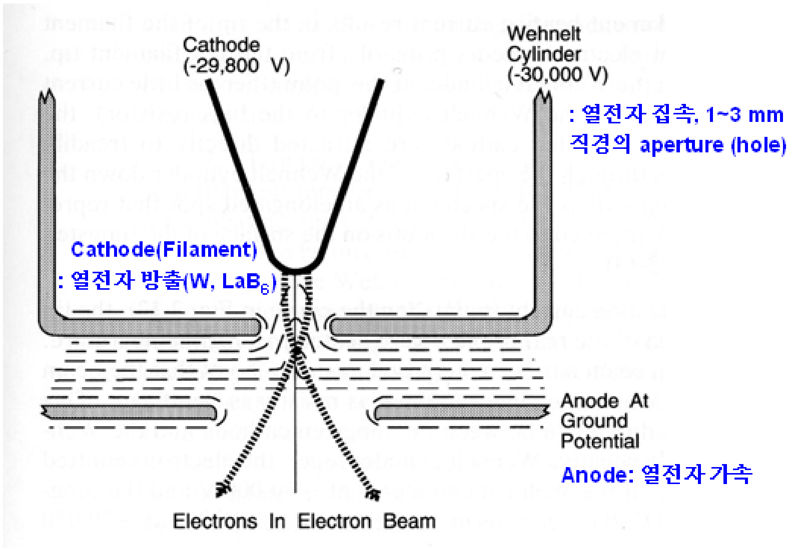
- change the direction of electrons
- magnifying (diverging) 발산
- diminishing (converging) 수렴
- condenser lenses, objective lenses,
- intermediate lenses, projection lenses



Electrostatic lenses: the Wehnelt cap

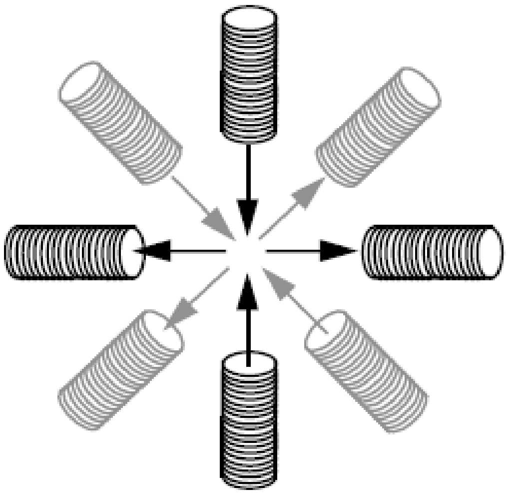
- Advantage
  - rotation free
- Disadvantage
  - high precision in construction
  - high precision in alignment
  - extreme cleanliness

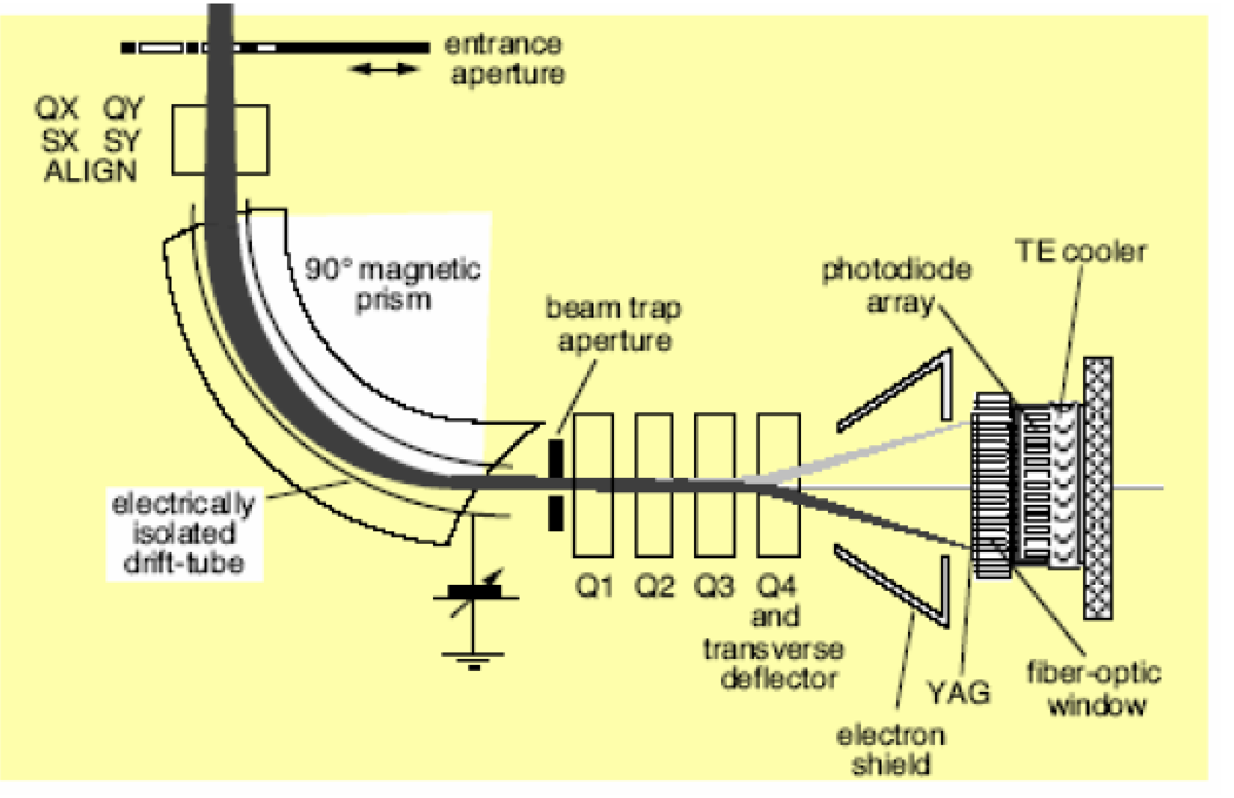
Thermionic Electron Emission Gun



Pole Lenses

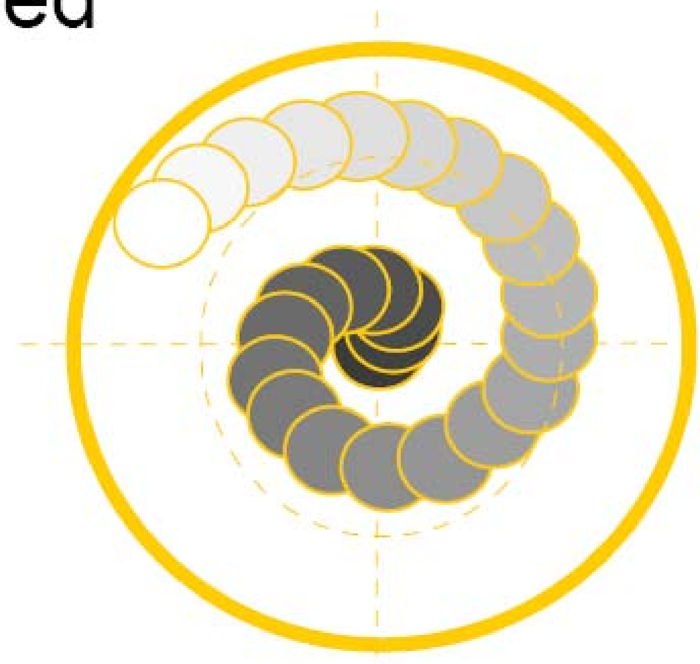
- Pole lenses are all electromagnetic, no electrostatic
- Different magnifying power in X, Y direction is possible
- The construction is just like the stigmators
- Usually seen in Cs correctors and EELS **(Electron Energy Loss Spectroscopy)**
- Qudrapole, Hexapole, Octupole lenses are common.





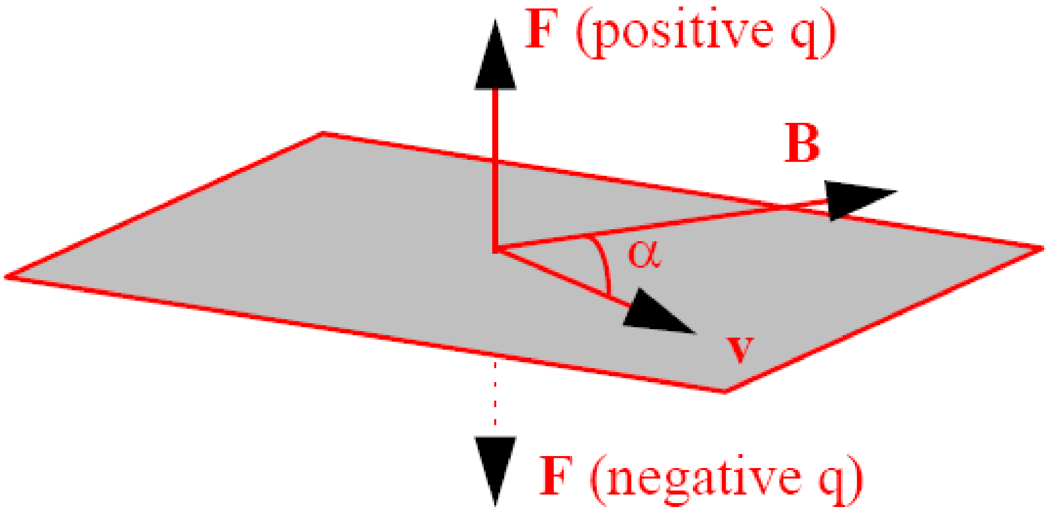
Lenses

- Electromagnetic lenses are based on the fact the moving electrons are forced into a spiral trajectory, i.e. focused into one point



Lenses

- Working Principle: Lorenz Force
  - electrons are only *deflected* by magnetic fields



Electromagnetic Lenses for Electrons

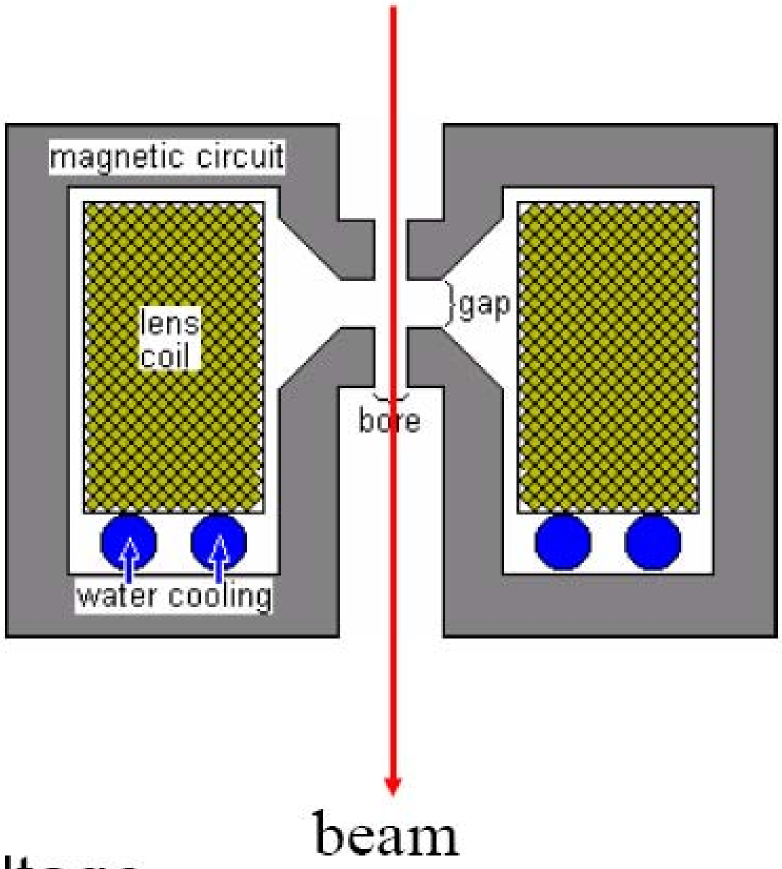
- Focus
- Magnification and demagnification
- Electron trajectory changed by magnetic field
- **F** = - e **v** x **B**
- F = evB sinθ
- If **v** // **B**, F = 0

$$R = \frac{m_0 v}{eB}$$

Lenses

- the focal length is given by:

$$f = \frac{K \cdot U}{(N \cdot I)^2}$$



K : constant

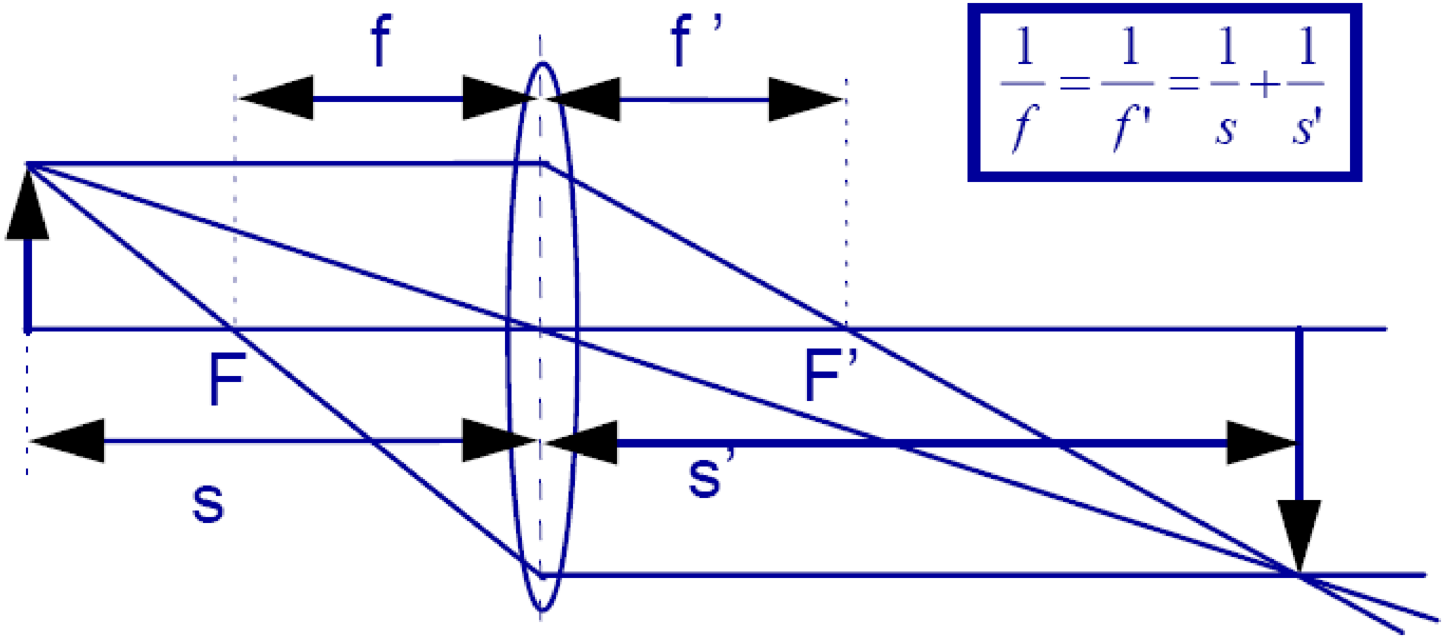
U : accelerating voltage

N : windings 굴곡

I : lens current

Lenses

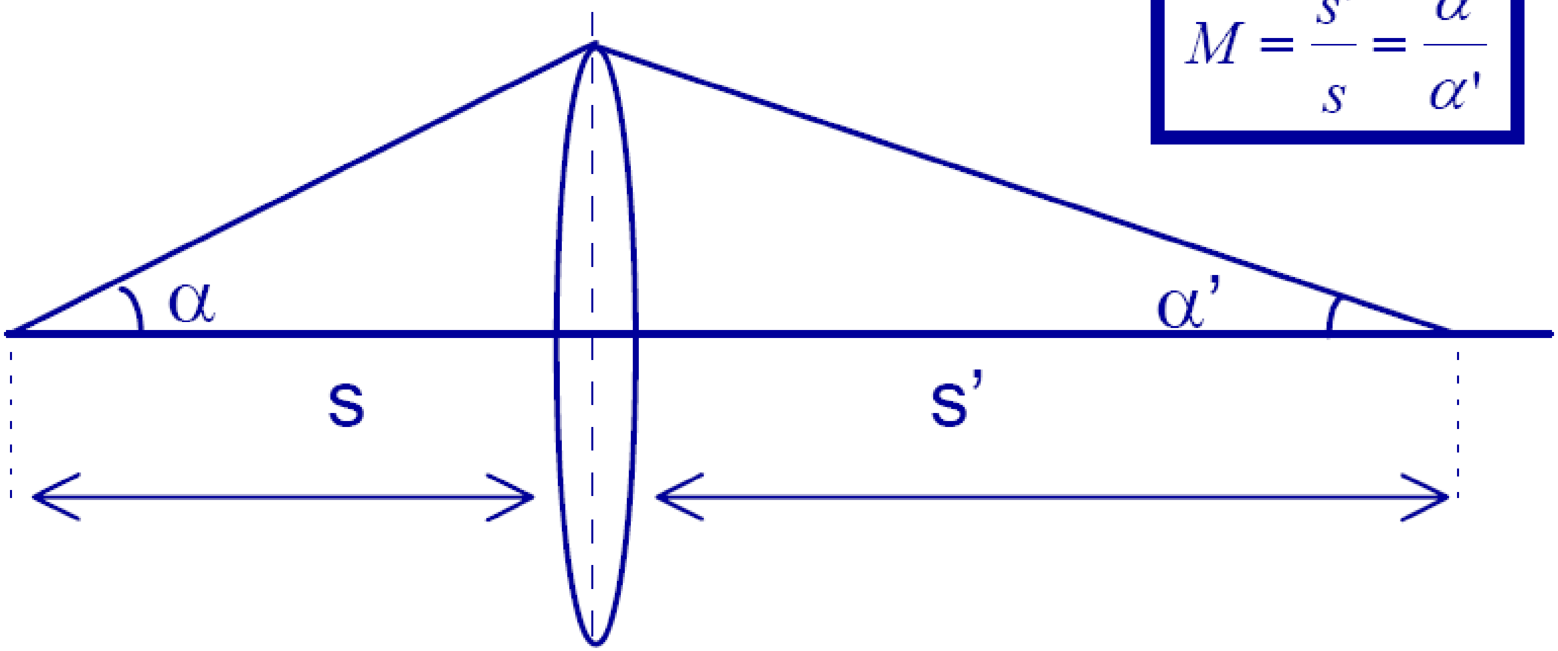
- Gaussian Law



Lenses

- Gaussian Law

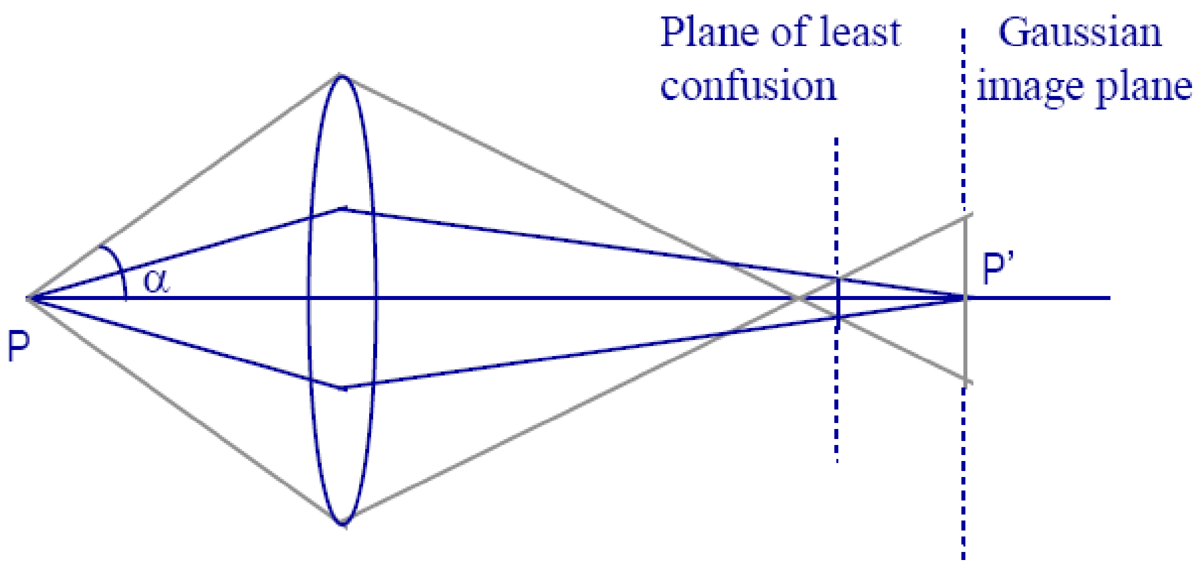
$$M = \frac{s'}{s} = \frac{\alpha}{\alpha'}$$



Lenses
Spherical Aberration

$$\delta_s = C_s \alpha^3$$

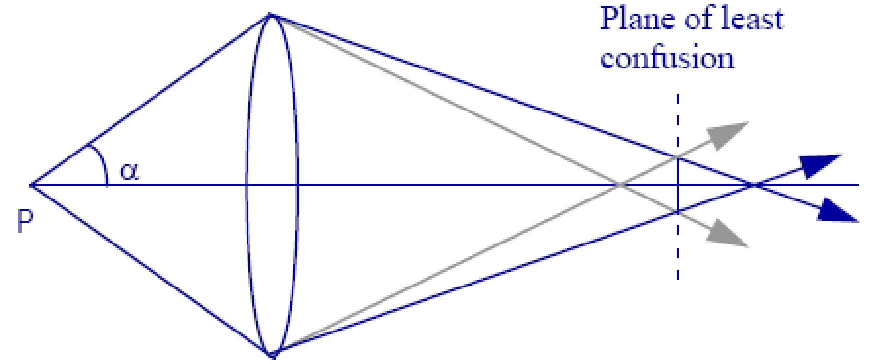
- Lens imperfections lead to different focal lengths in centre and at edges of lens



Outer zones have stronger strengths

Lenses
Chromatic Aberration

- Blurring due to energy spread in electron beam and lens current fluctuations

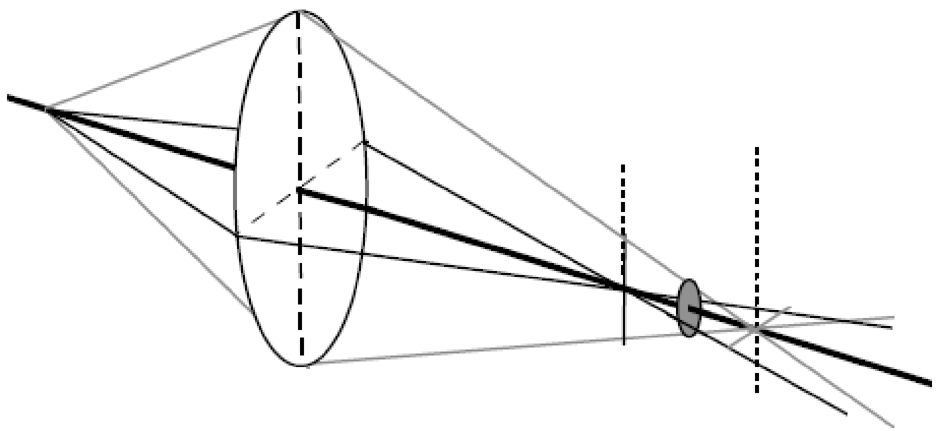


$$\delta_c = C_c \alpha \left(\frac{\Delta E}{E} + \frac{2\Delta I}{I} \right)$$

Lenses

Astigmatism

- Lens defect caused by magnetic field asymmetry



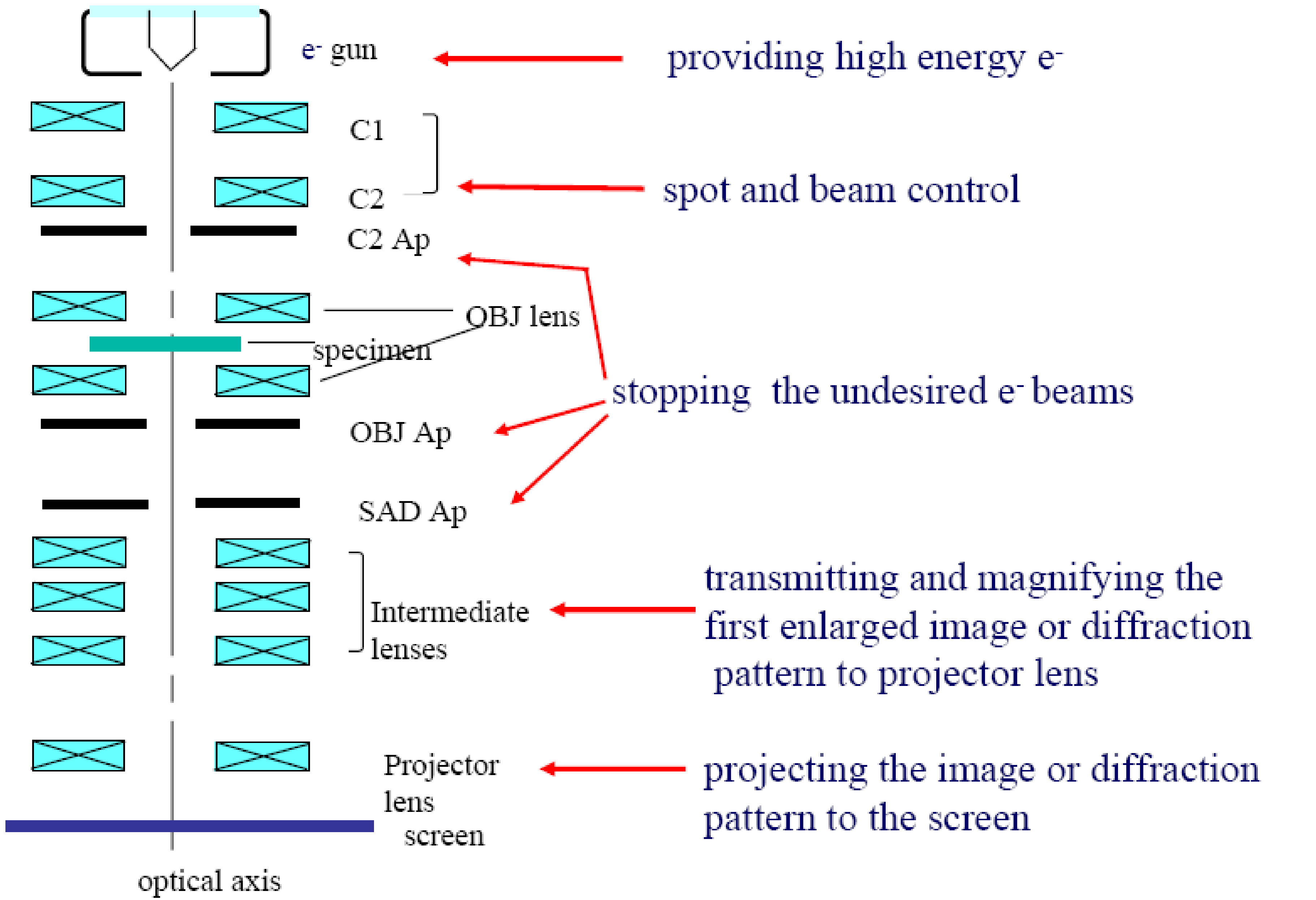
- can be corrected using stigmators!

Lens System

- Condenser C1Lens
- Condenser C2 Lens
- Objective Lens

- Imaging Lenses (TEM)
  - diffraction (1st intermediate lens)
  - intermediate
  - projector

Lens System of TEM



Lens System
Condenser C1 and C2

- C1
  - strong demagnifying lens
  - spotsize setting
- C2
  - weak lens
  - intensity control

Lens System & Microscope Resolution

- Microscope resolution is governed by: (for TEM)
  - wavelength of electrons
  - C_s of objective lens
  - other lenses are less crucial (α/M)

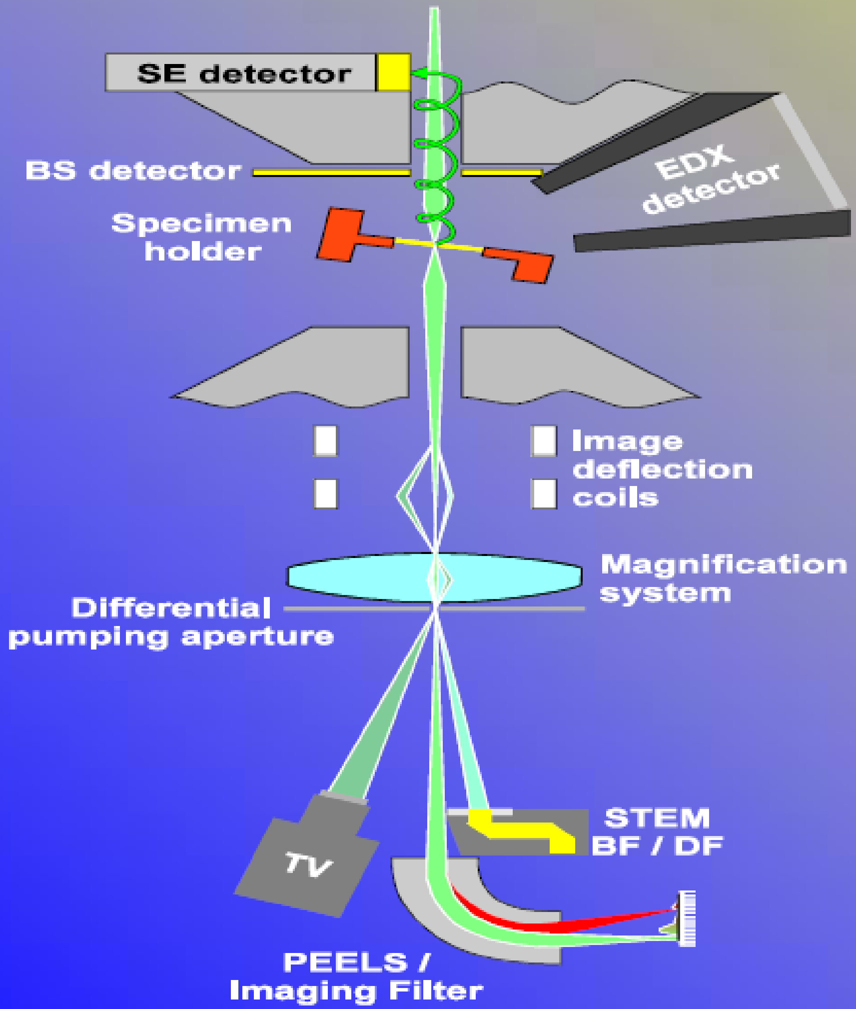
$$\delta = 0.66 \times C_s^{1/4} \lambda^{3/4}$$

Stigmators

- Provide means to correct for deficiencies in the magnetic lenses

- EM stigmators:
  - At condenser, objective and diffraction lens (TEM)
  - At condenser, objective (SEM)
  - closely positioned to the lenses

Signals and Detectors



- In TEM
  - Energy Filter
  - TV / CCD camera
  - Plate camera
- In STEM
  - BF / DF
  - HAADF
  - BS & SE (SEM)
- In STEM and TEM
  - EDX and PEELS