2009 spring

Microstructural Characterization of Materials

04. 08. 2009

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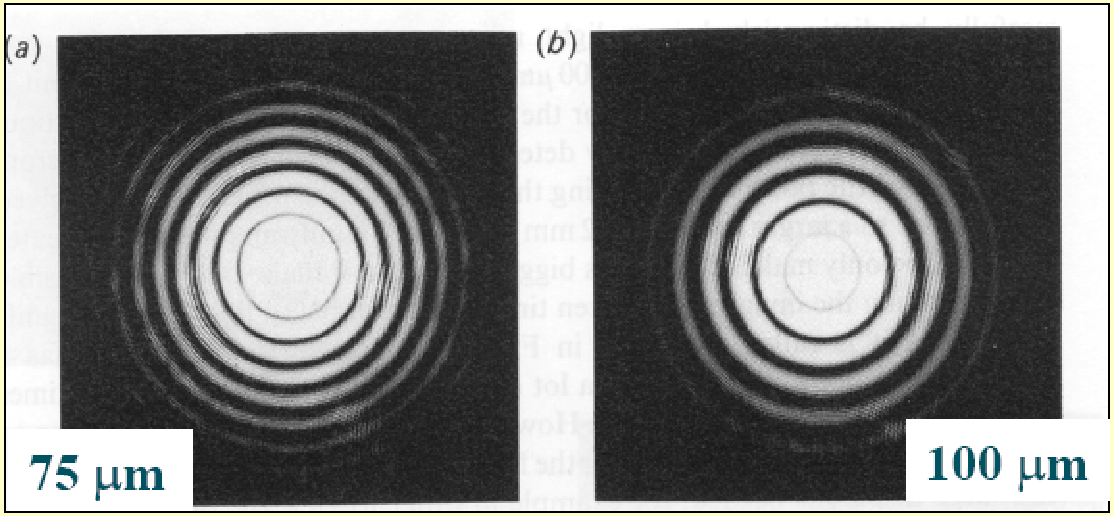
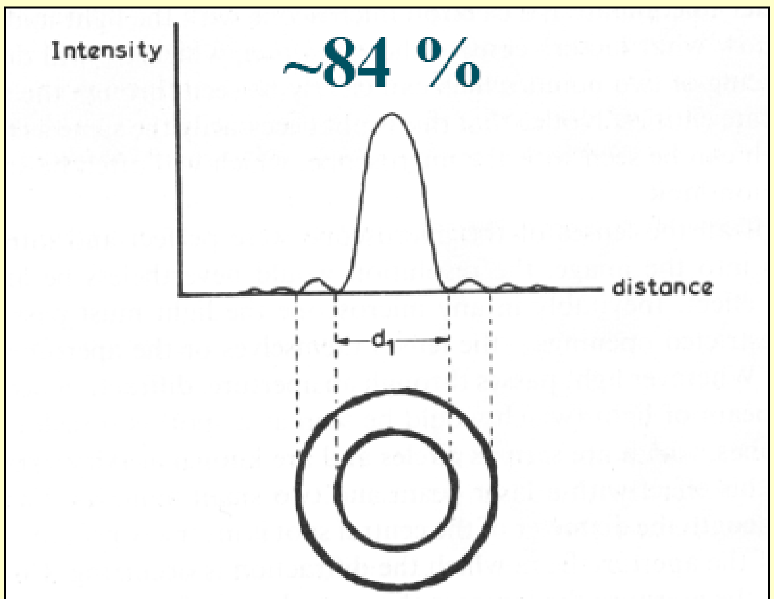
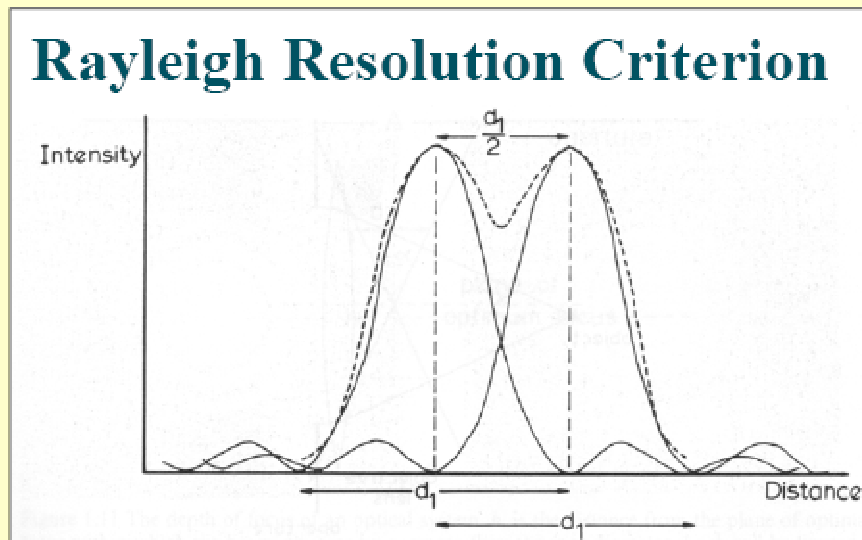
Resolution … Airy Discs



Laser beam Diffraction through a pinhole

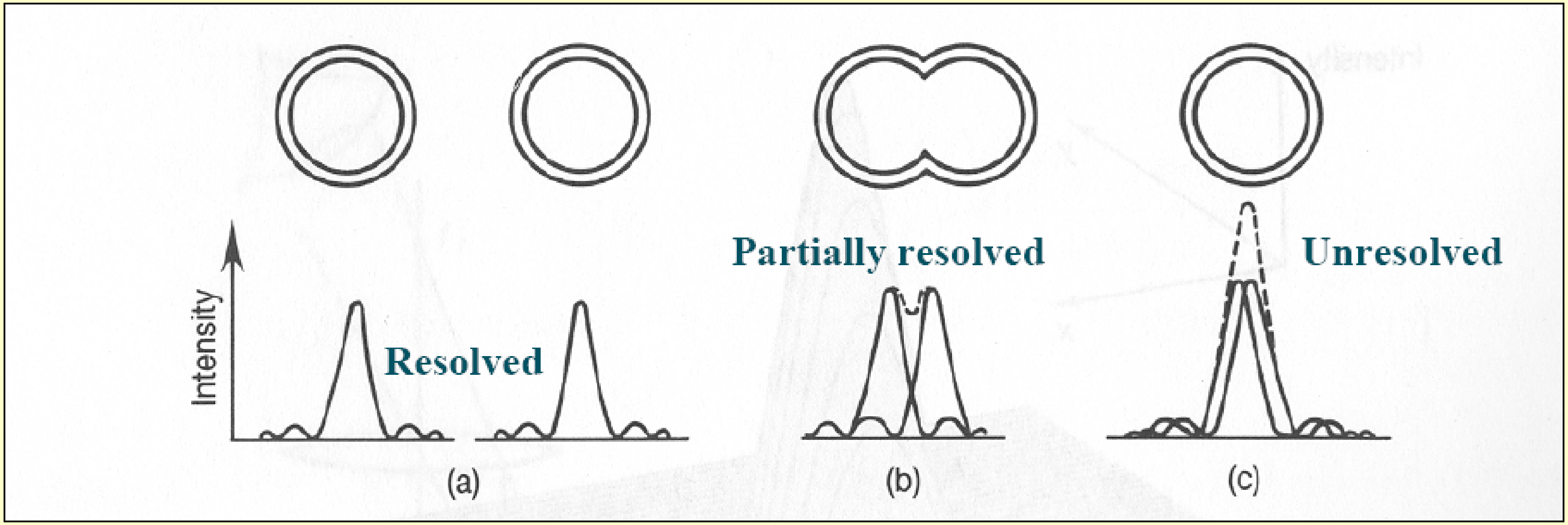




$d_1 \sim 1/\text{aperture-diameter}$

$R_1 = d_1/2 = 0.61\lambda/n\sin(\alpha) = 0.61\lambda/NA$

Diffraction limited Resolution



Thus the smallest separation is determined by the N.A. (1/2f#)

Typically the best objective has N.A ≈1.6 ⇒ resolution ≈170 nm

For λ~400 nm (green light)

⇒ Decrease λ

Electron Microscopy - Decreasing The Wavelength

$$\Rightarrow \quad E = \frac{p^2}{2m} = eV$$ **Energy Conservation**

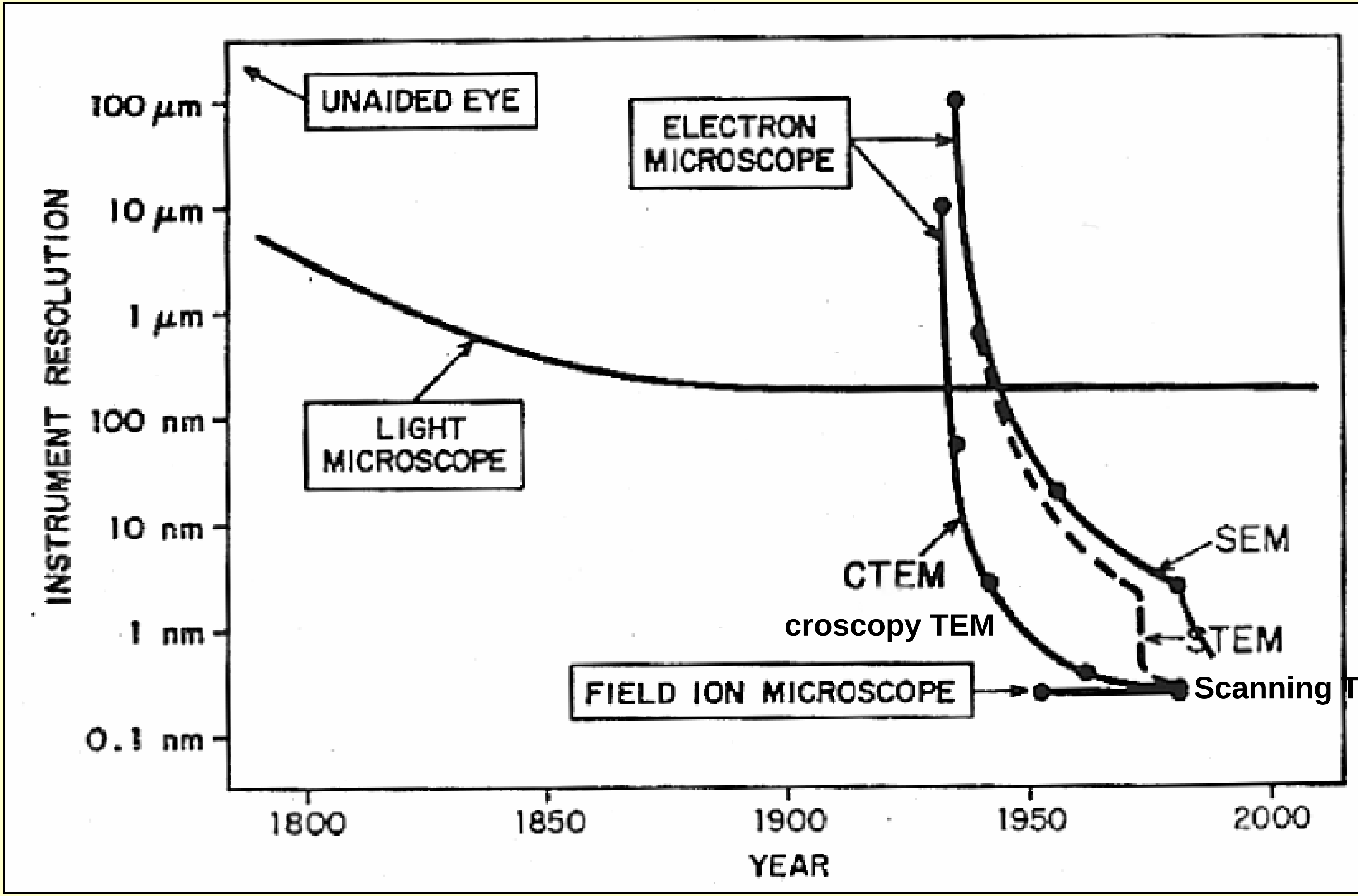
$$\Rightarrow \quad p = \sqrt{2meV}$$

$$P = \frac{h}{\lambda}$$

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}} = \frac{6.6 \cdot 10^{-34}}{\sqrt{2 \cdot 9.1 \cdot 10^{-31} \cdot 1.6 \cdot 10^{-19} \cdot 50000}} \approx 0.05\,\mathring{A}$$

Resolution (50 kV): $R_1 = 0.61\lambda/NA \sim (0.6 \bullet 0.05)/1.6 \sim 0.2$ Å

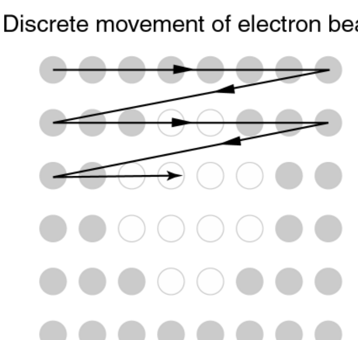
The Evolution of Resolution

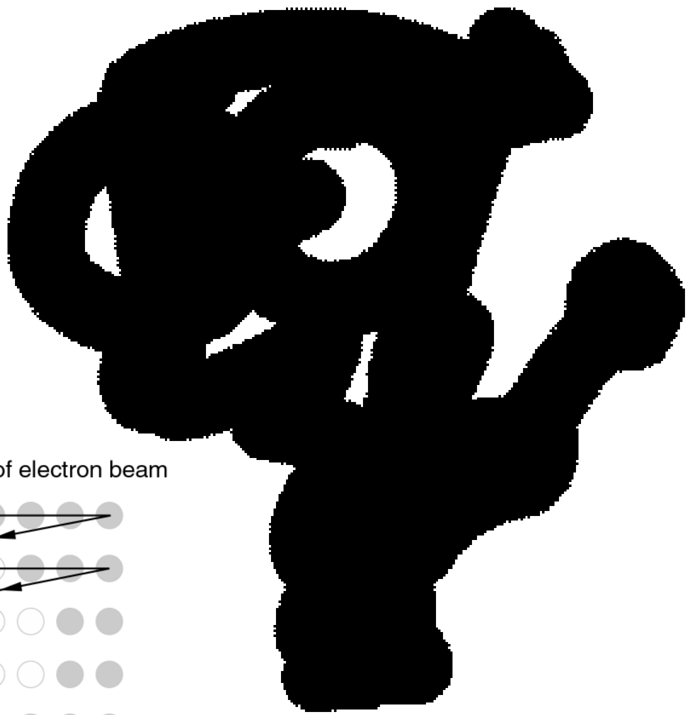


광학현미경과 전자현미경의 비교

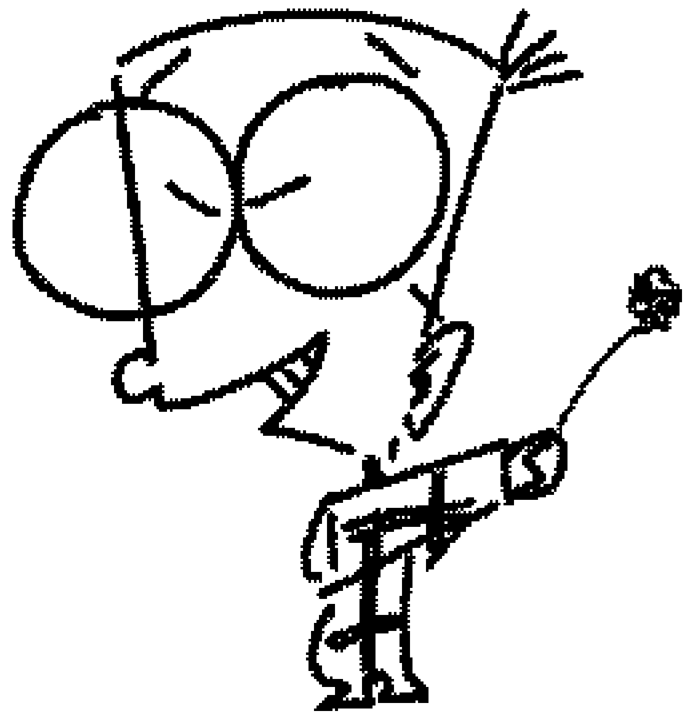
항 목	전자현미경	광학현미경
광 원	전자빔	가시광선
파 장	**0.0859 Å (20KV) ~** **0.0251 Å (200KV)**	**7,500 Å**(가시광선)~ **2,000 Å**(자외선)
전파매질	진 공	공 기
렌즈(방법)	전자기렌즈	유리렌즈
분해능	점분해능 : **3.5 Å** 회절격자분해능 : **1.4 Å**	가시광선 : **2000 Å** 자외선 : **1000 Å**
사용배율	**100X ~ 450,000X**	**10X ~ 2,000X**
초점조절	전기적	기계적

Effect of Probe Size : Impact on Resolution



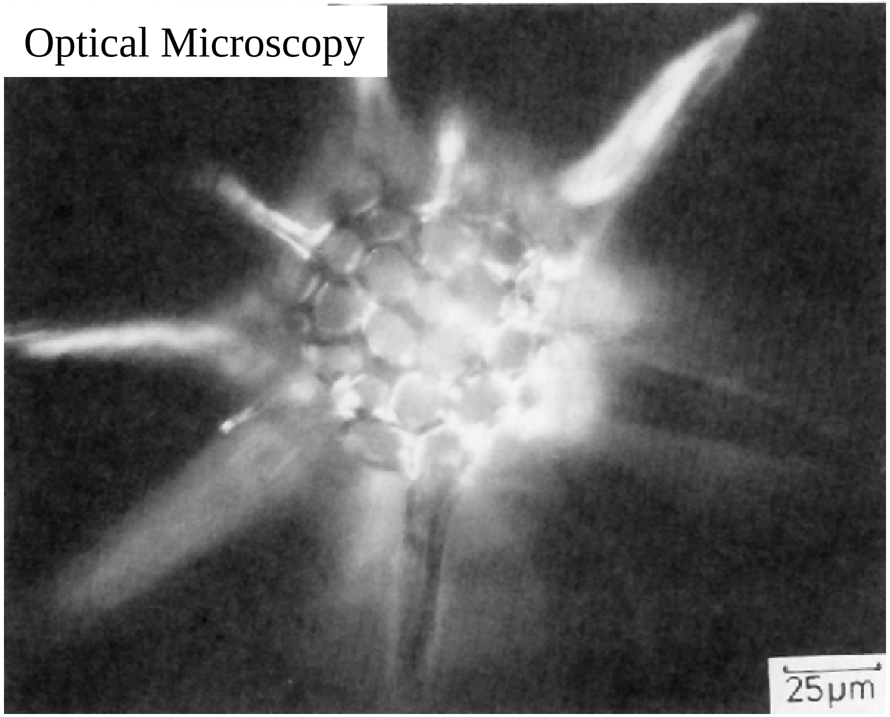


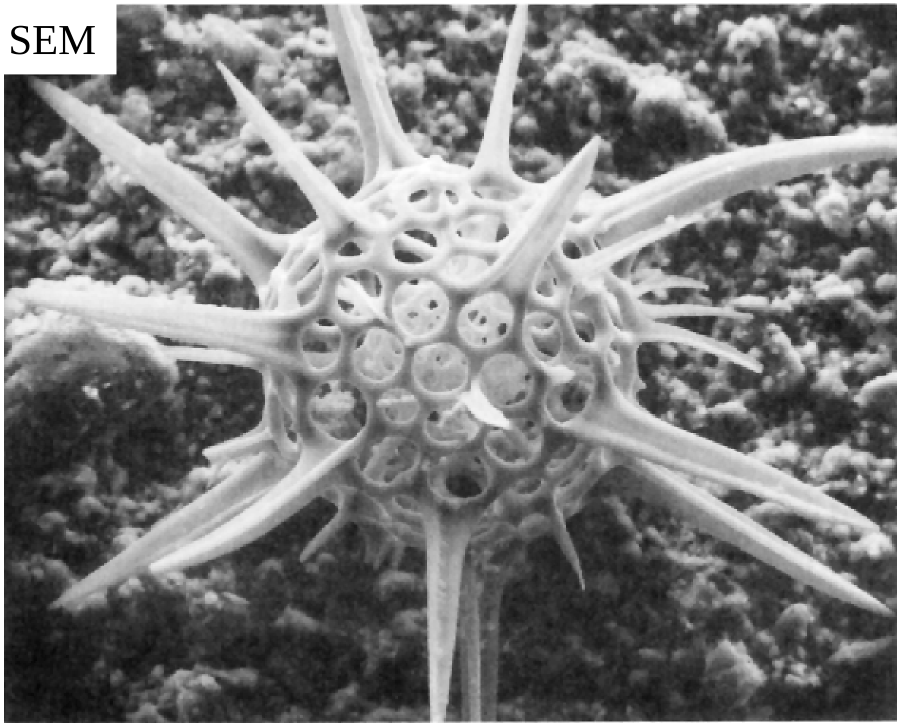
With large probe



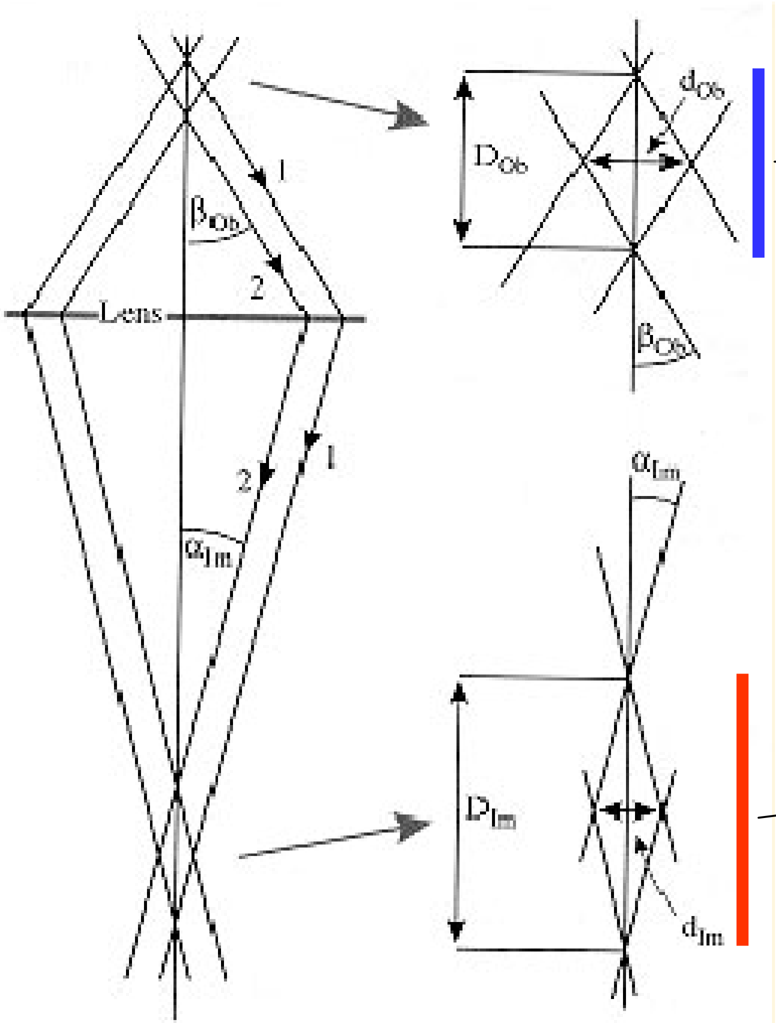
With small probe

Optical vs. Electron Microscopy





Depth of focus



$$D_{ob} = \frac{d_{ob}}{\beta_{ob}}$$

: 물체 심도
Depth of field

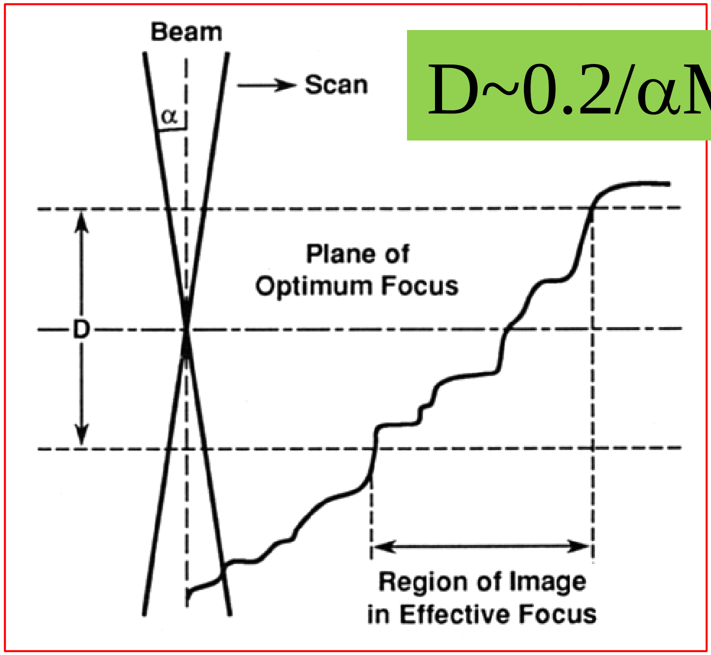
$$D_{ob} = d_{ob}/\tan \beta_{ob}$$
$$= d_{ob}/ \beta_{ob}$$

$$D_{im} = \frac{d_{ob}}{\beta_{ob}} M_T^2$$

: 초점 심도
Depth of focus

$$D_{im} = d_{im}/\tan \alpha_{im}$$
$$= d_{im}/ \alpha_{im}$$
$$= D_{ob}\ M_T^2$$
$$= d_{ob}\, M_T^{\,2}/ \beta_{ob}$$

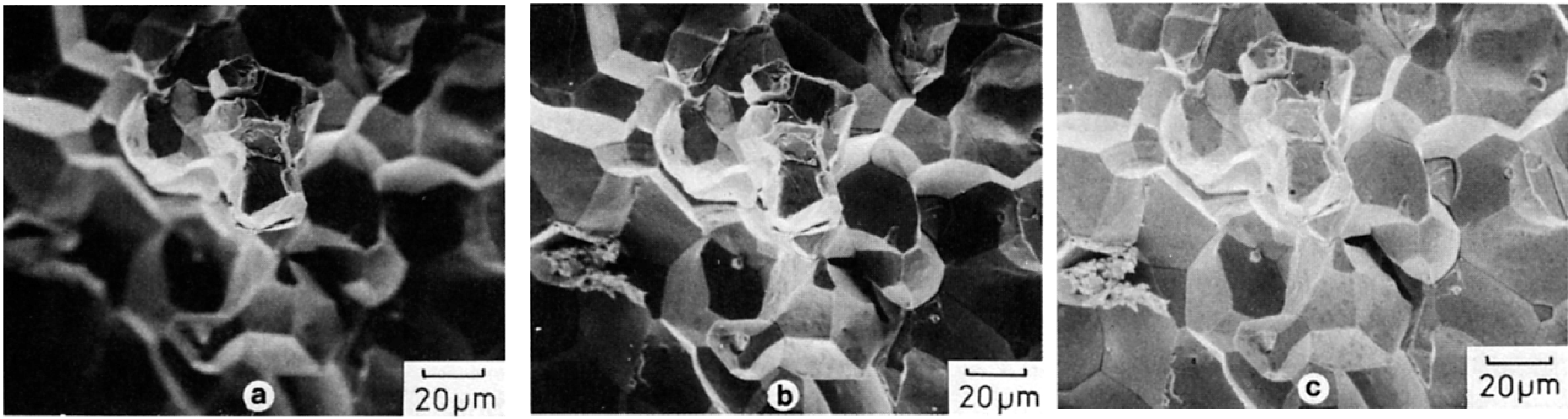
Depth of focus



$D \sim 0.2/\alpha M$

Table 4.3. Depth of Focus (Field) in μm

Magnification	α (rad)		
	5×10^{-3}	1×10^{-2}	3×10^{-2}
10X	4,000	2,000	670
50X	800	400	133
100X	400	200	67
500X	80	40	13
1,000X	40	20	6.7
10,000X	4	2	0.67
100,000X	0.4	0.2	0.067



전자기렌즈에 의한 분해능의 한계

Ideal Res. Limit : Rayleigh limit

Practical Res. is determined by various Lens aberrations

$$d = \sqrt{d_d^2 + d_s^2 + d_c^2 + d_a^2}$$

Negligible d_c, d_a

$$d = \sqrt{d_d^2 + d_s^2}$$

$$d_d = \frac{0.61\lambda}{\alpha}$$

Diffraction 수차

$$d_s = C_s \alpha^3 M$$

C_s : 구면수차 계수

$$d_a = \alpha^3 \triangle f$$

Astigmatism: stigmator로 보정

$$d_c = C_c \alpha \frac{\triangle E}{E}$$

C_C : 색수차 계수

ΔE : 0.2-0.3eV for cold FE

Spherical aberration and aperture diffraction vary in opposite directions with α. This leads to the need to find an optimum aperture angle α_{opt}.

SEM - scanning electron microscopy

tiny electron beam scanned across surface of specimen

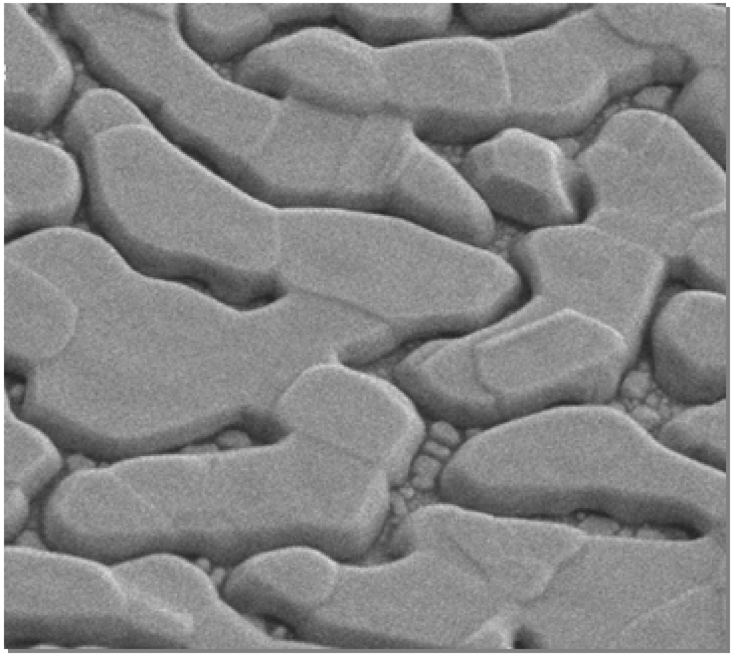
backscattered or secondary electrons detected

Magnification range 15x to 200,000x

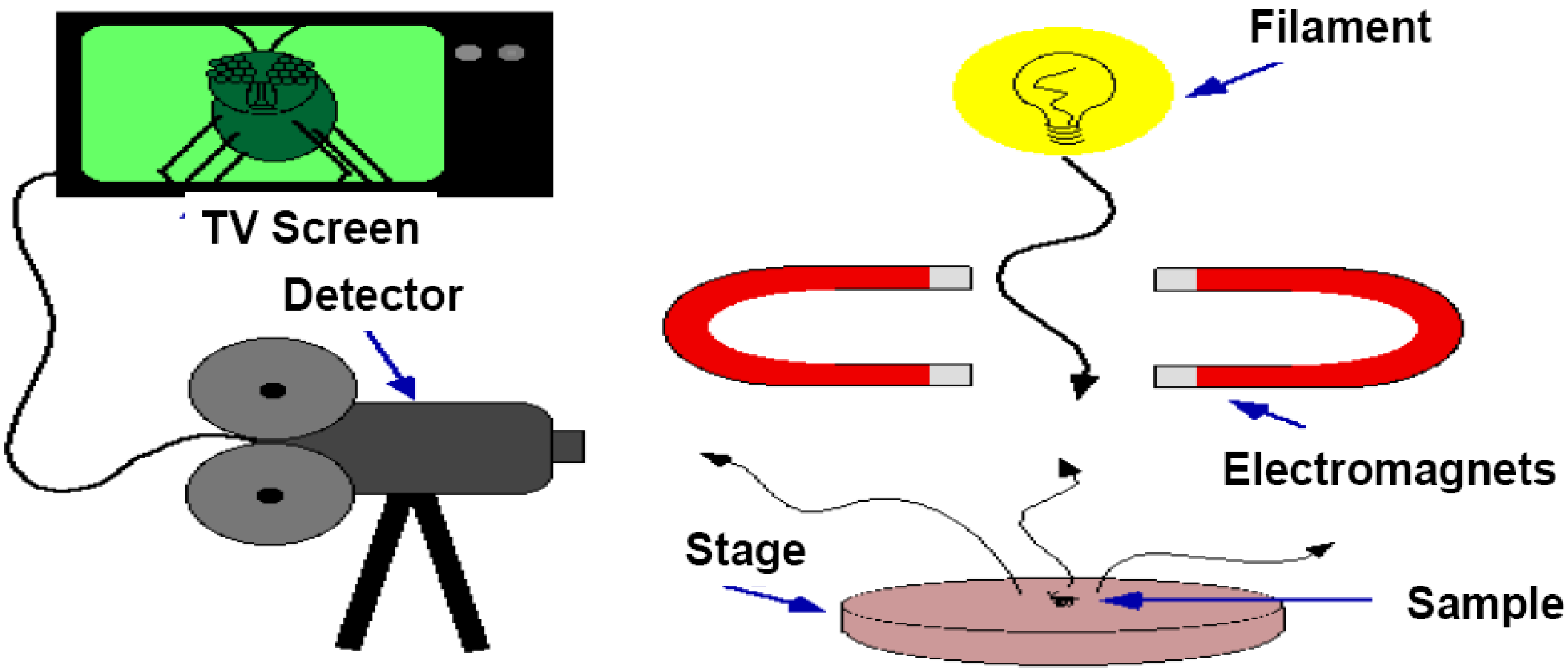
Resolution of 50 Å

Excellent depth of focus

Relatively easy sample prep

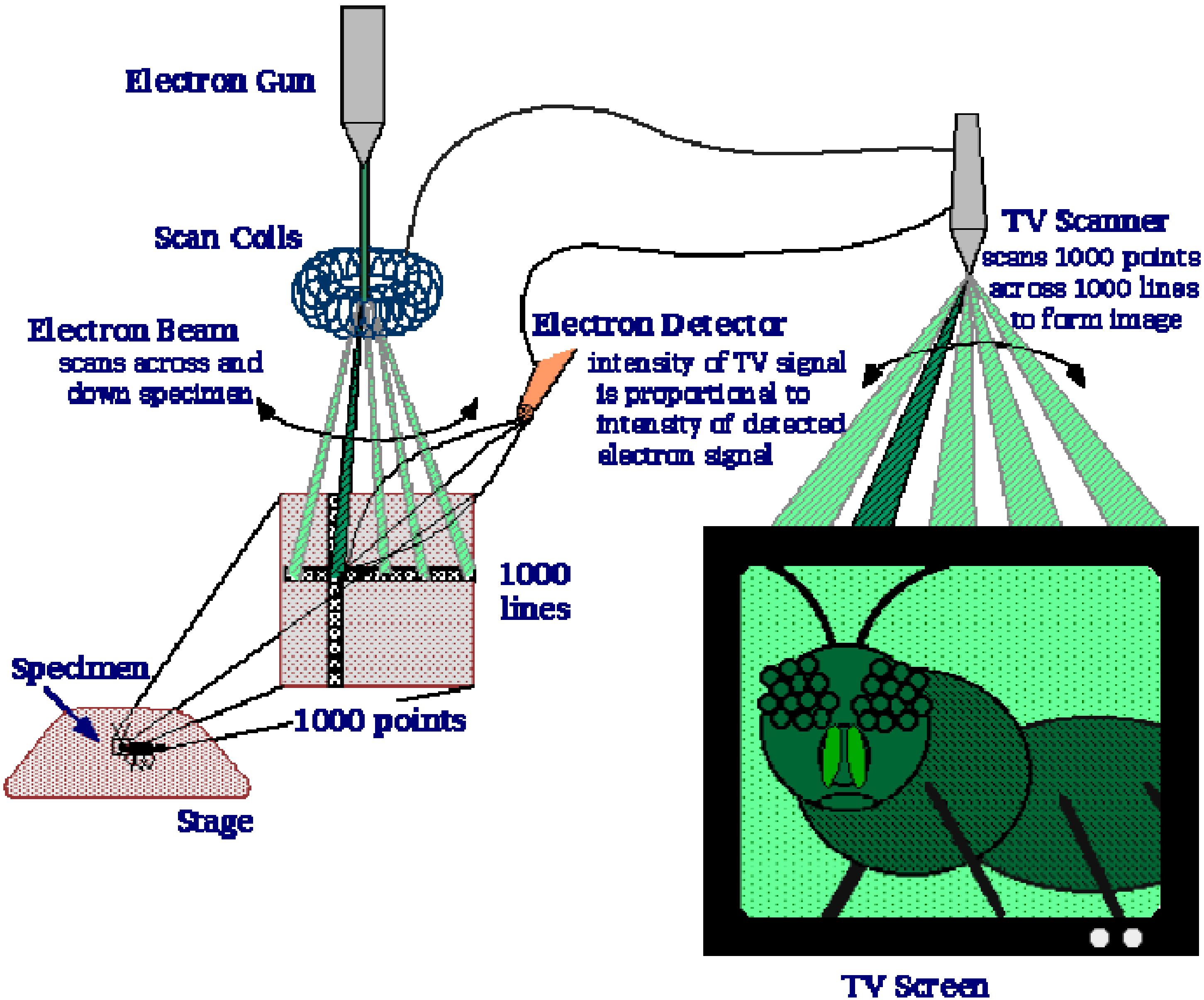


Breakdown of an electron microscope

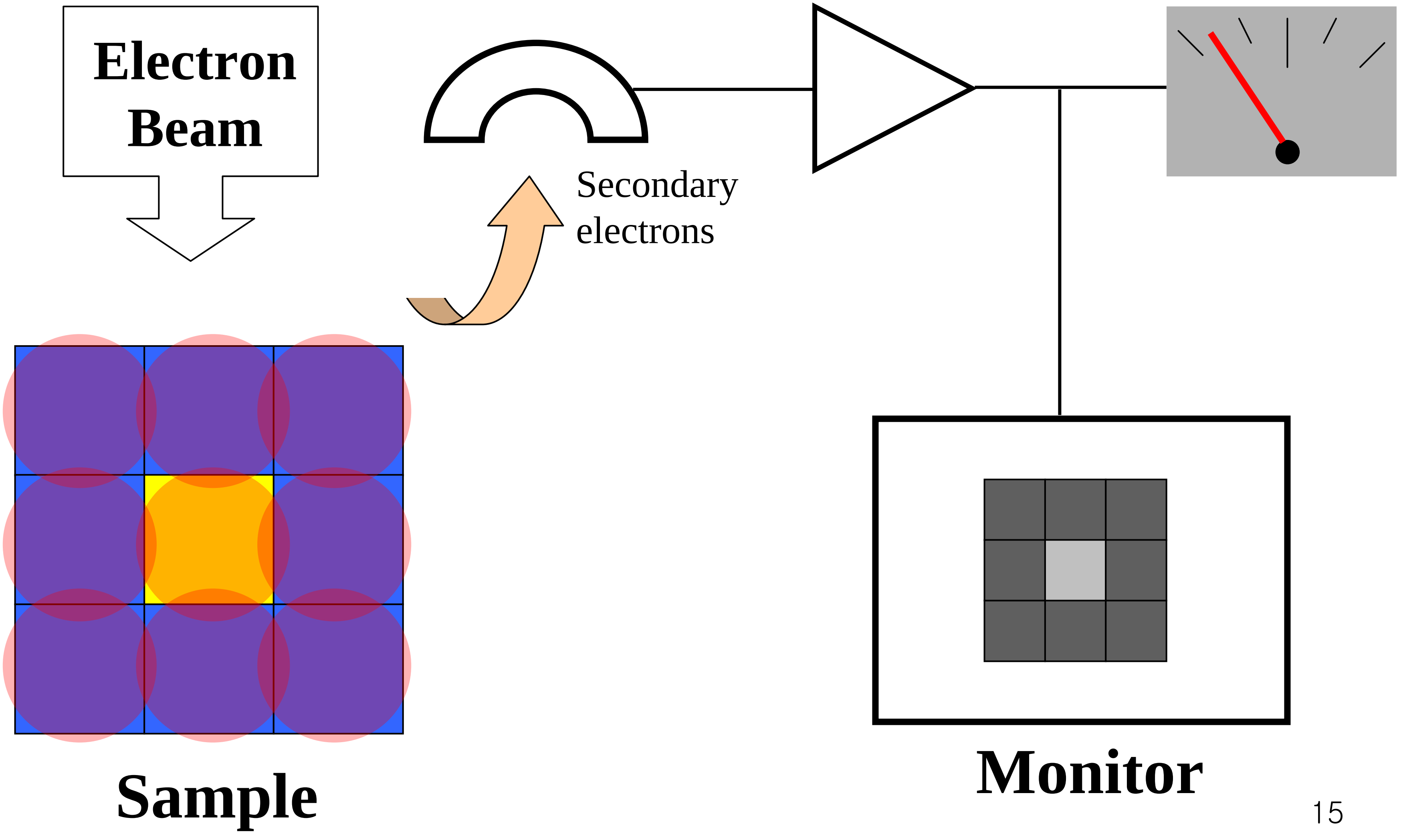


In simplest terms, an SEM is really nothing more than a television. We use a filament to get electrons, magnets to move them around, and a detector acts like a camera to produce an image.

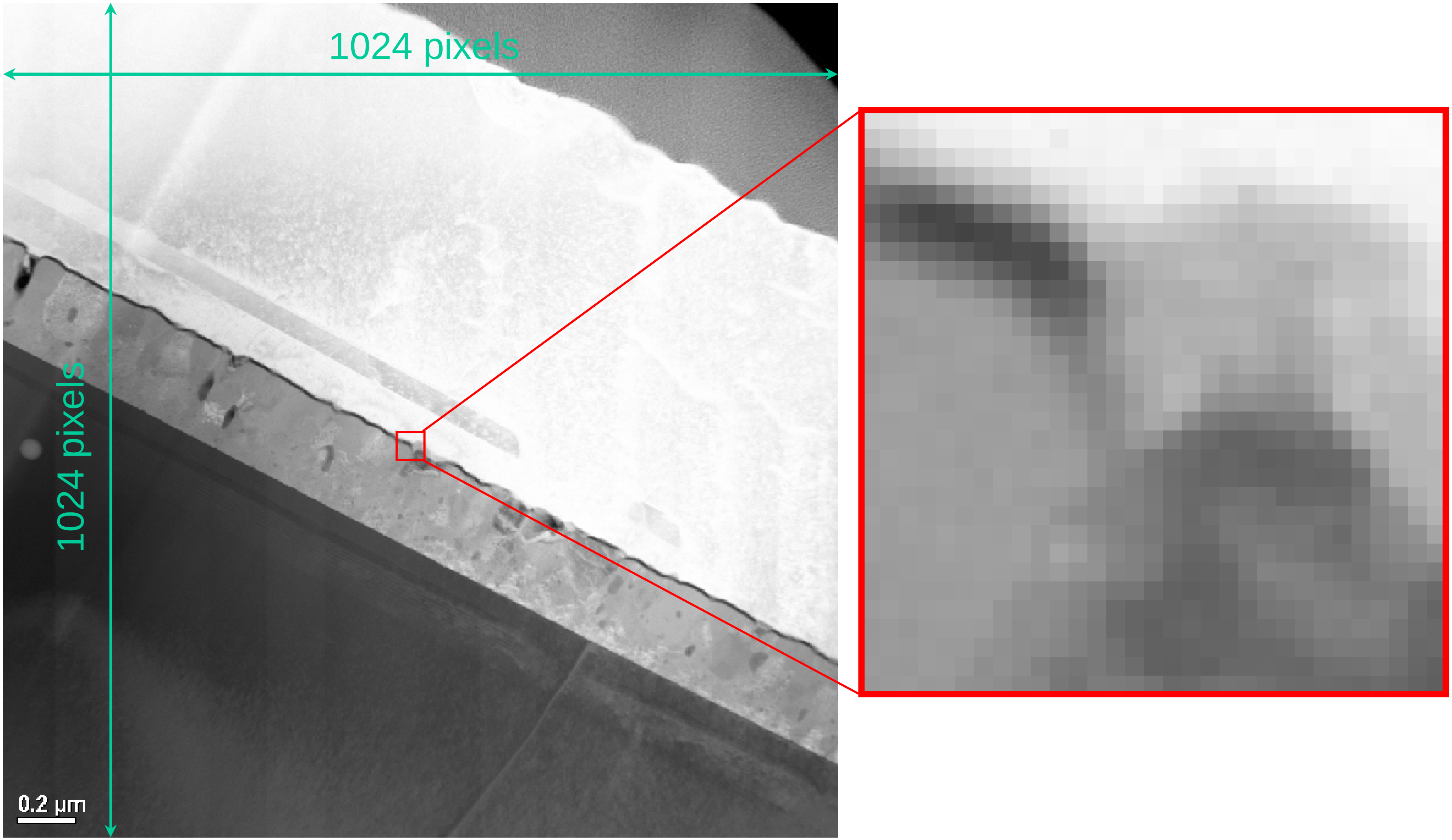
SEM Operation



Scanning Technology

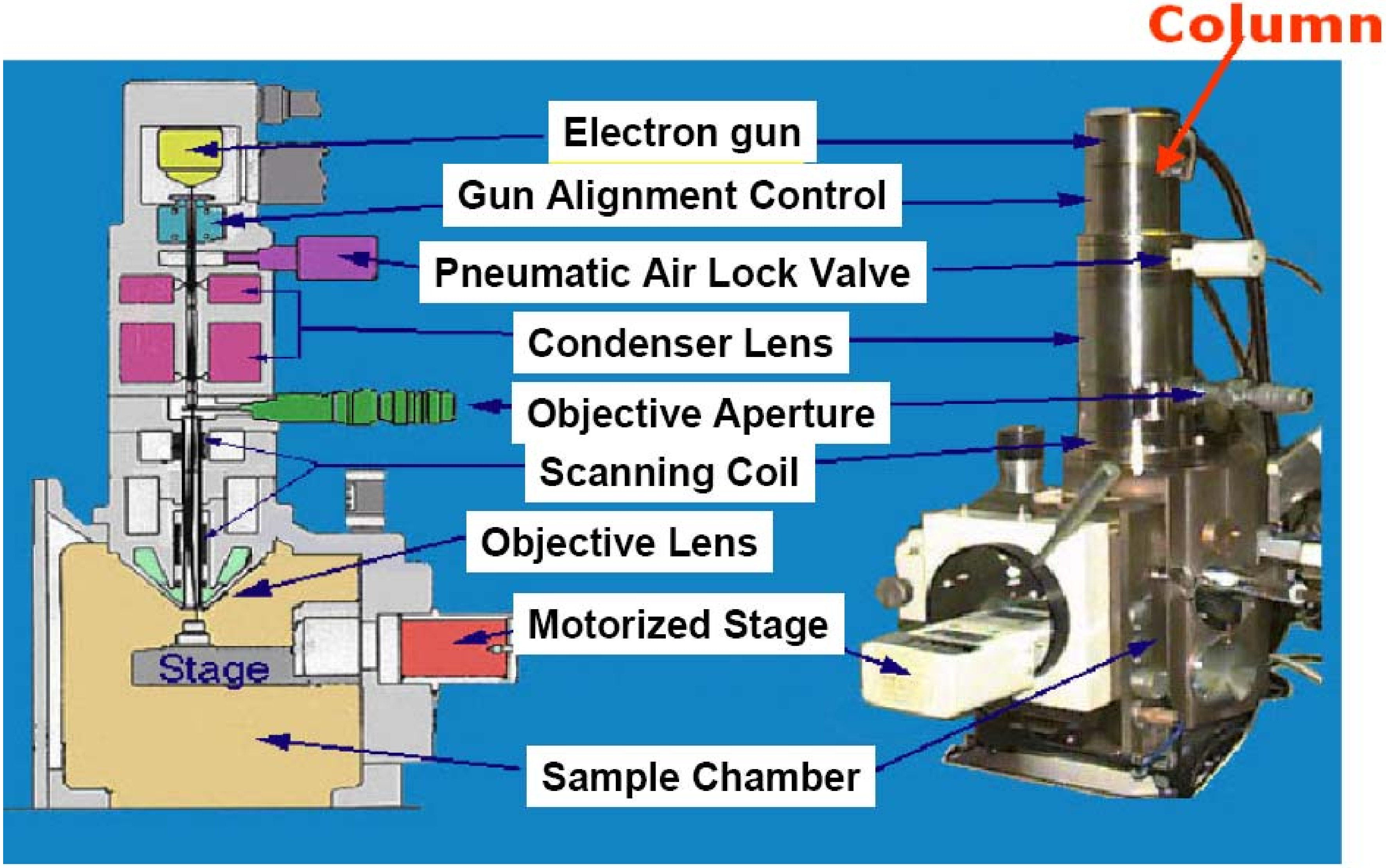


Pixel by pixel image



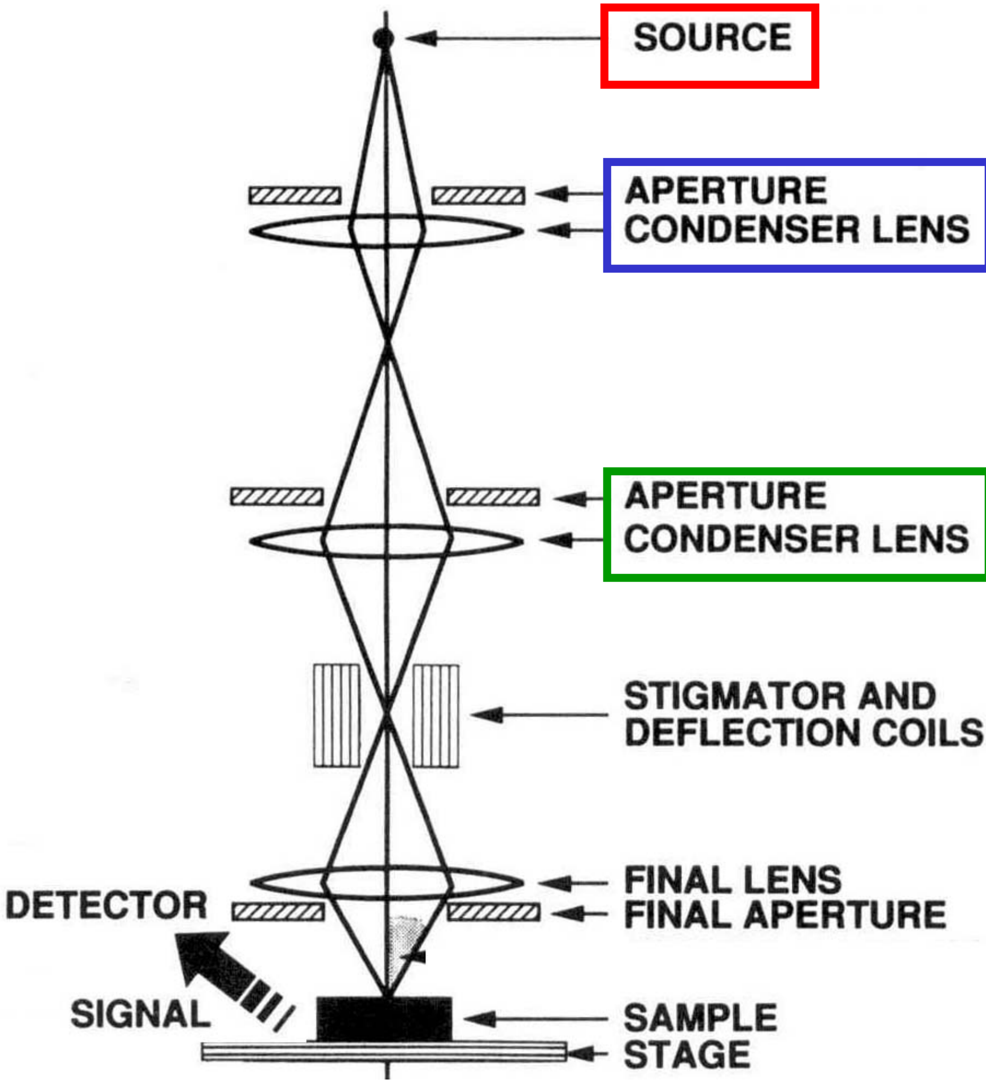
Digital Z-contrast image

A look inside the column



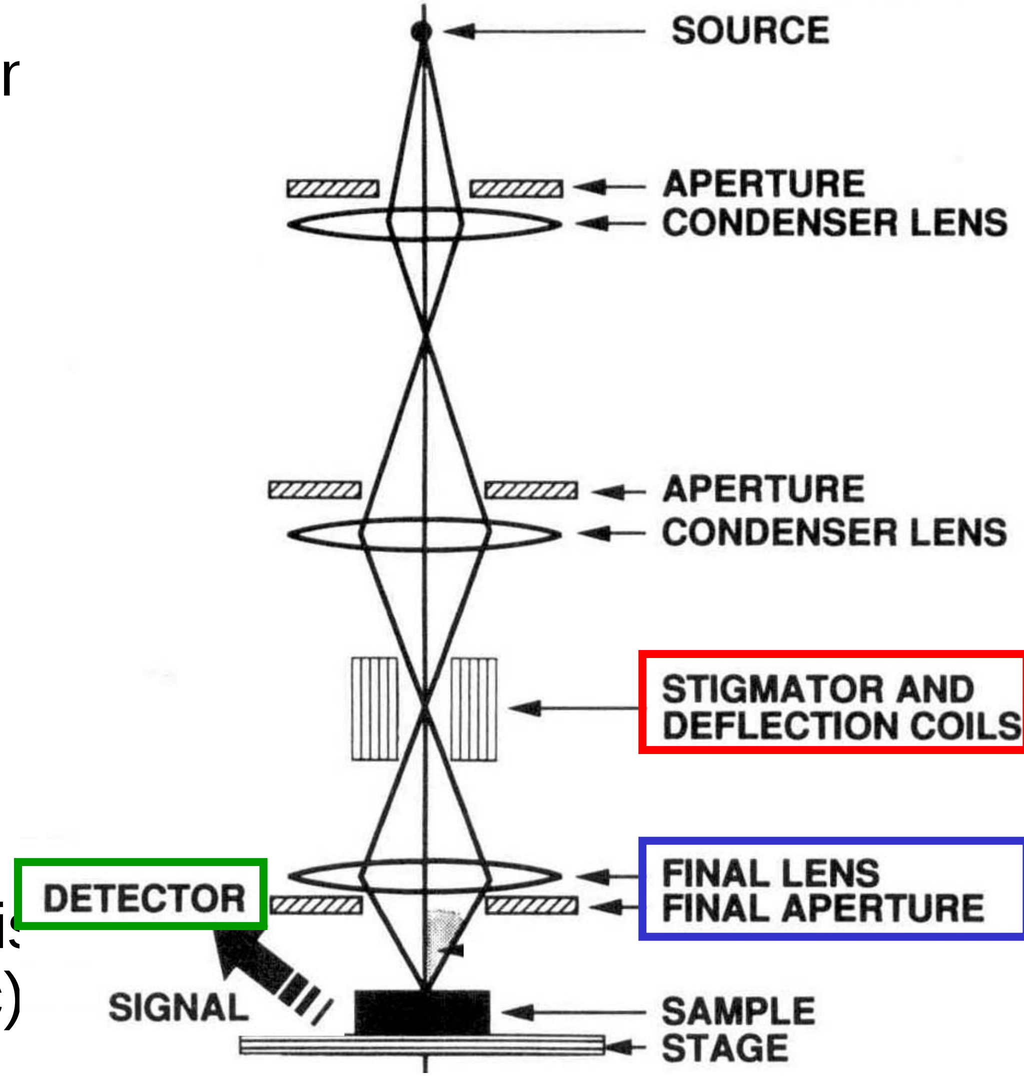
SEM: Optics #1

- Electron gun produces beam of monochromatic electrons.
- First condenser lens forms beam and limits current ("coarse knob").
  - Condenser aperture eliminates high-angle electrons.
- Second condenser lens forms thinner, coherent beam ("fine knob").
  - Objective aperture further eliminates high-angle electrons from beam.



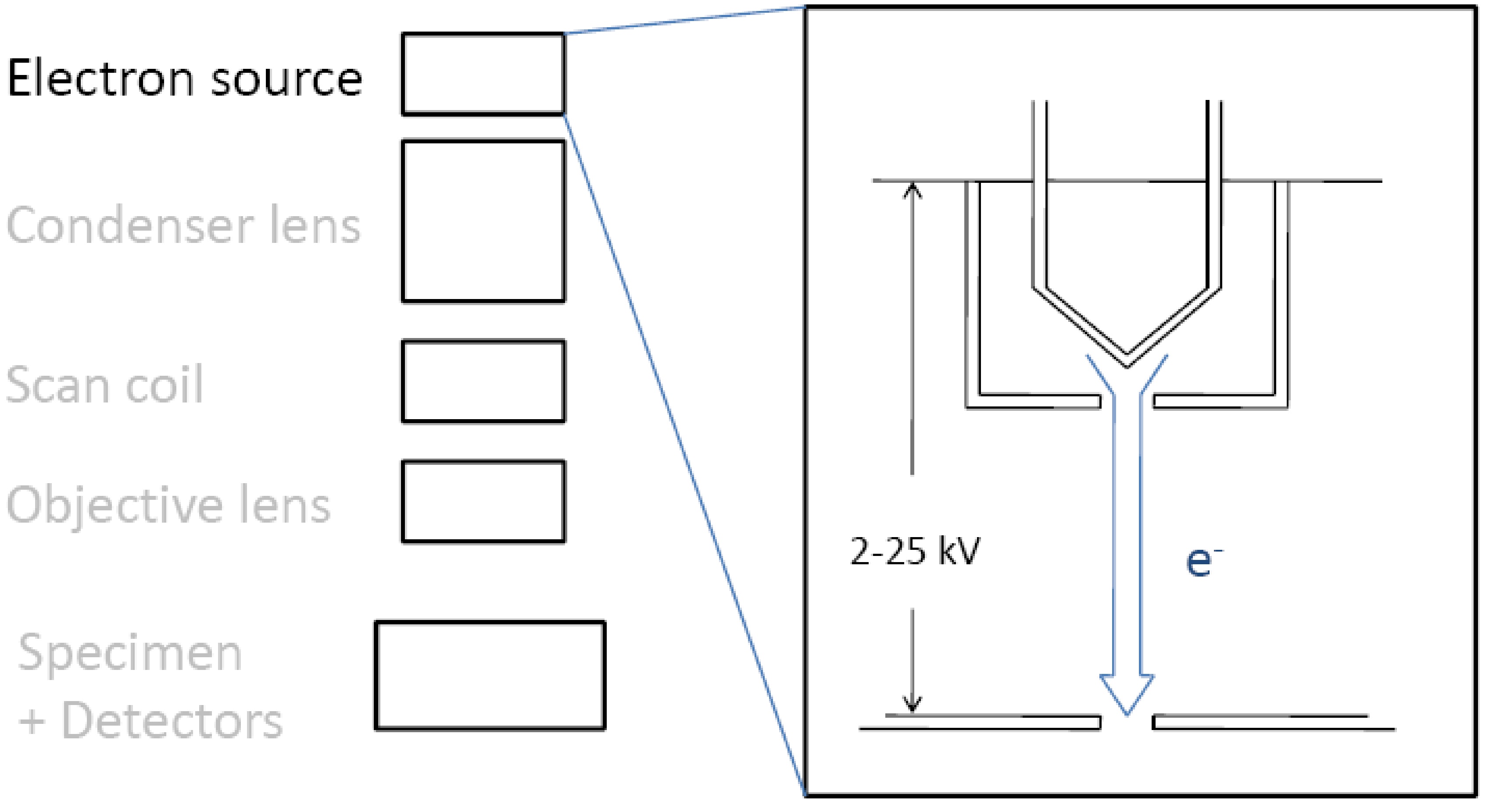
SEM: Optics #2

- Beam "scanned" by deflectior coils to form image.
- Final objective lens focuses beam onto specimen.
- Beam interacts with sample and outgoing electrons are detected.
- Detector counts electrons at given location and displays intensity.
- Process repeated until scan is finished (usu. 30 frames/ sec)



http://www.unl.edu/CMRAcfem/semoptic.htm

Electron Gun (전자빔)

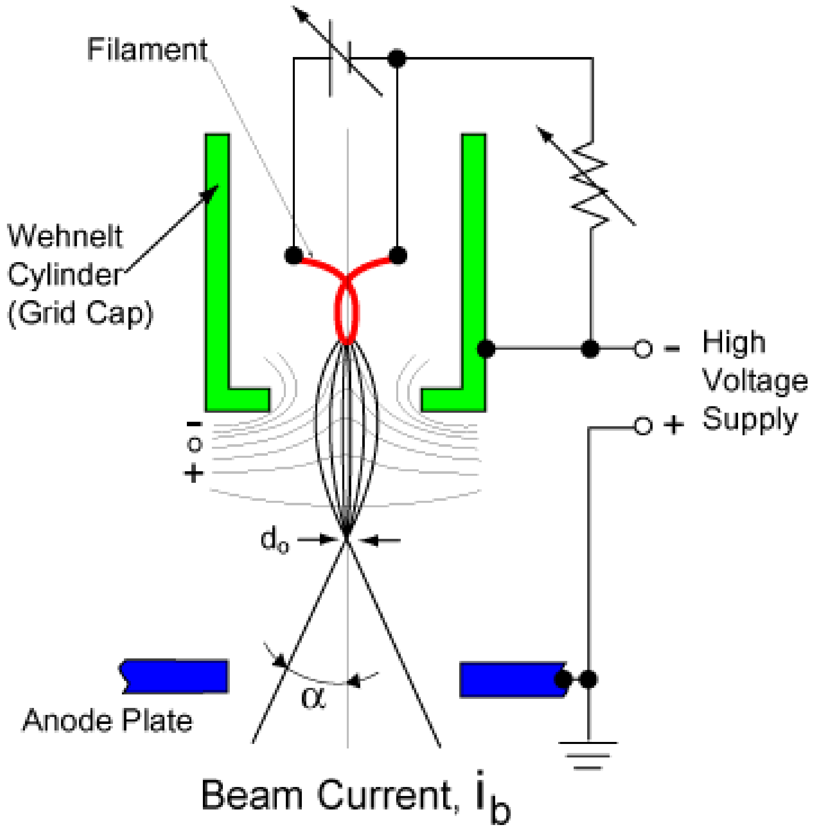


Electron Emission-electron gun

- Cathode of the gun is the source of electrons for the beam in the electron microscope

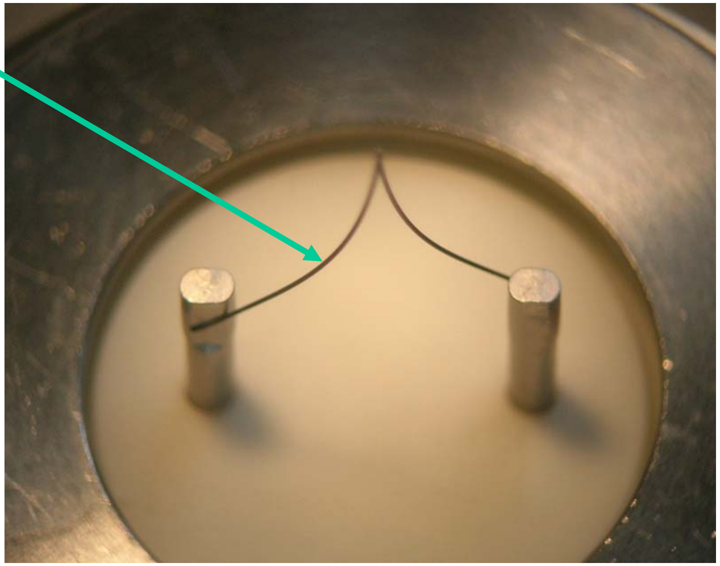
- Thermionic emission – heat
- Field emission – strong electrical field
- Photoelectric emission – electromagnetic radiation

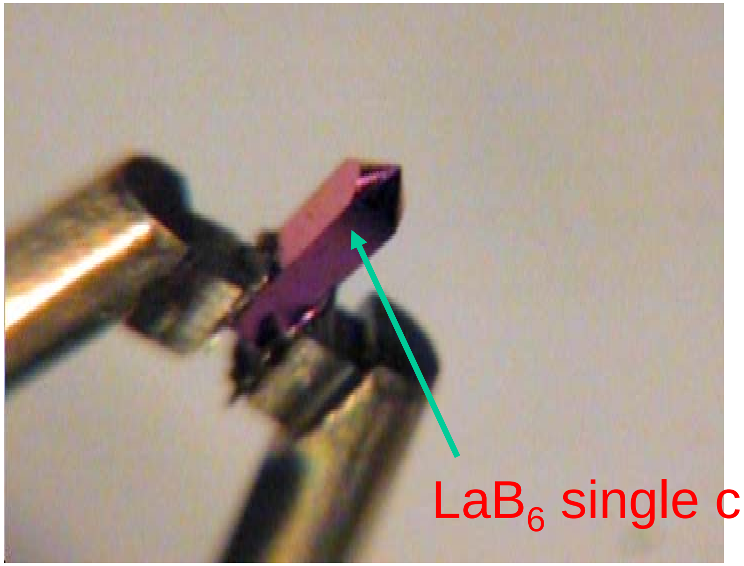
Thermionic Emission



Self biasing from a resistor

Tungsten Hairpin





LaB_6 single crystal

Thermionic Emission(열전자 방출)

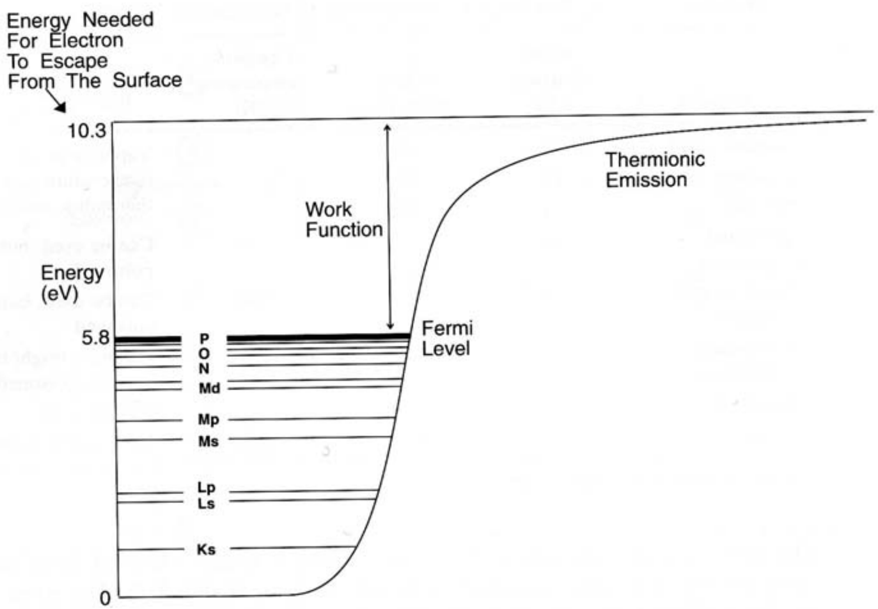


Figure 2-3 Thermionic emission curve of tungsten. Diagram of the energy of the orbital electrons of tungsten showing that the work potential is the difference between the energy necessary for the electrons to escape from the surface of the metal and the energy of the highest-orbital electrons.

Work Function: 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

Orbital Electrons in Tungsten(W)

TABLE 2-1 CONFIGURATION OF THE ORBITAL ELECTRONS IN LANTHANUM AND TUNGSTEN ATOMS

	Atomic number	K	L		M			N				O			P
		s	*s*	*p*	*s*	*p*	*d*	*s*	*p*	*d*	*f*	*s*	*p*	*d*	*s*
Lanthanum	57	2	2	6	2	6	10	2	6	10		2	6	1	2
Tungsten	74	2	2	6	2	6	10	2	6	10	14	2	6	4	2

The electrons that are circled are far from the atomic nucleus and are the main contributors to thermionic emission.

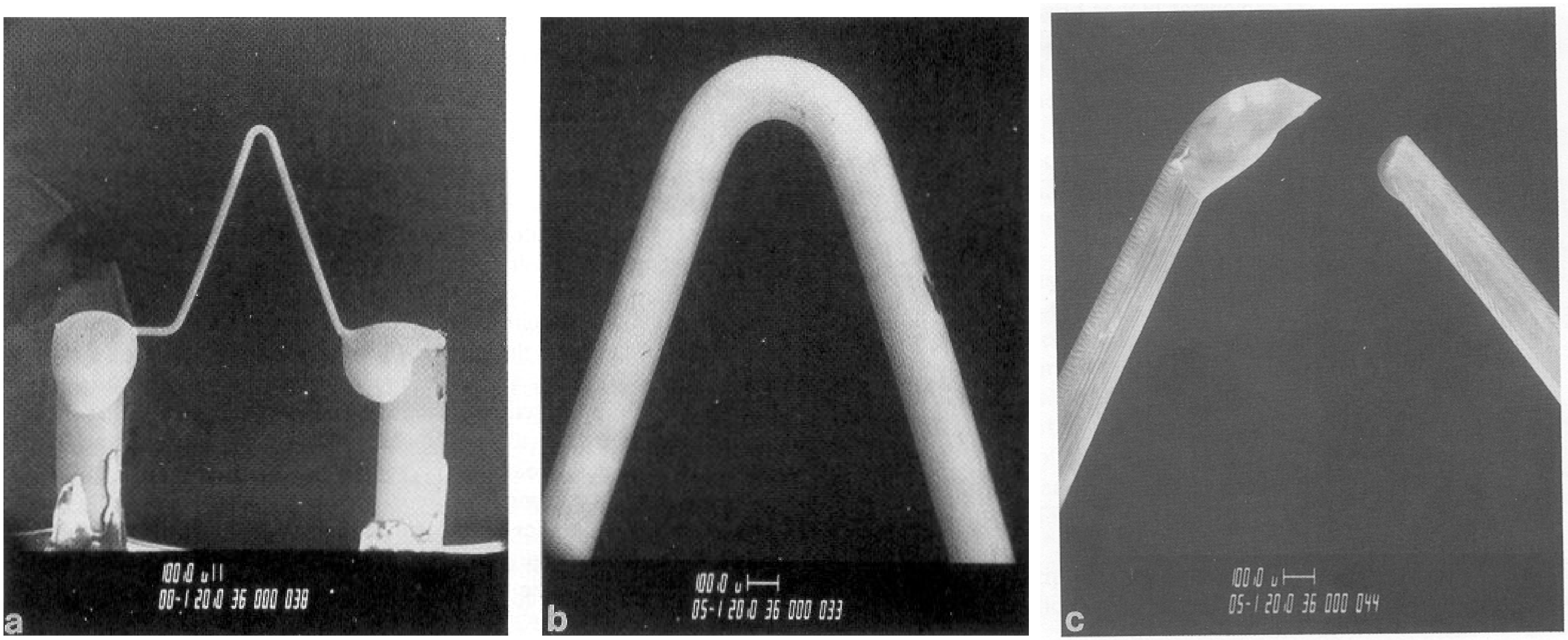
Negative electron은 원자의 positive nuclei 주위의 전자궤도 (orbit)에 속박되어 있다.

가장 바깥궤도에 있는 전자: valence electrons

작은 holding force와 높은 에너지를 가지므로 상대적으로 떼어내기 쉬우나, 낮은 표면탈출에 필요한 운동에너지가 적음

1. Tungsten Hairpin Electron Gun

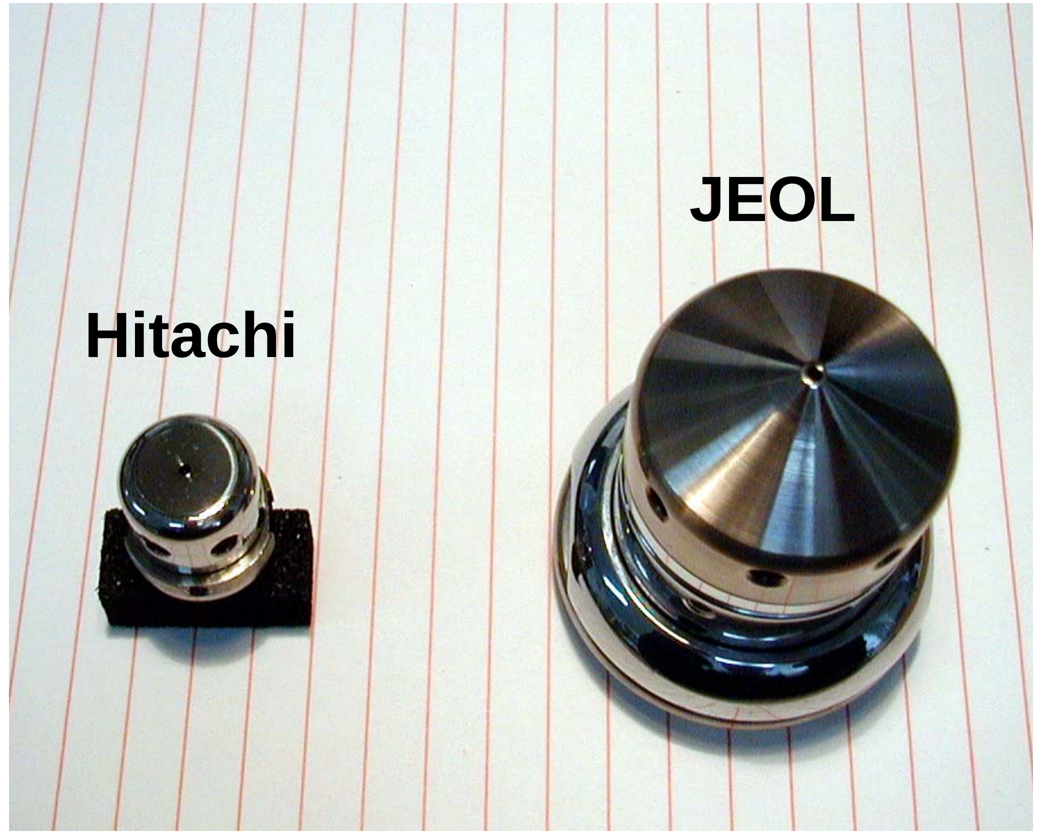
Inexpensive, low mag.
high current (x-ray microanalysis), low vacuum(10^{-5}torr), t=30-100h



V-shaped hairpin tip of d = 100μm

대부분의 금속 : 열전자 방출 전에 용융, 융점이 높은 W 사용

Electron source assembly



Removed Wehnelt cap

Electron Gun(W-filament)

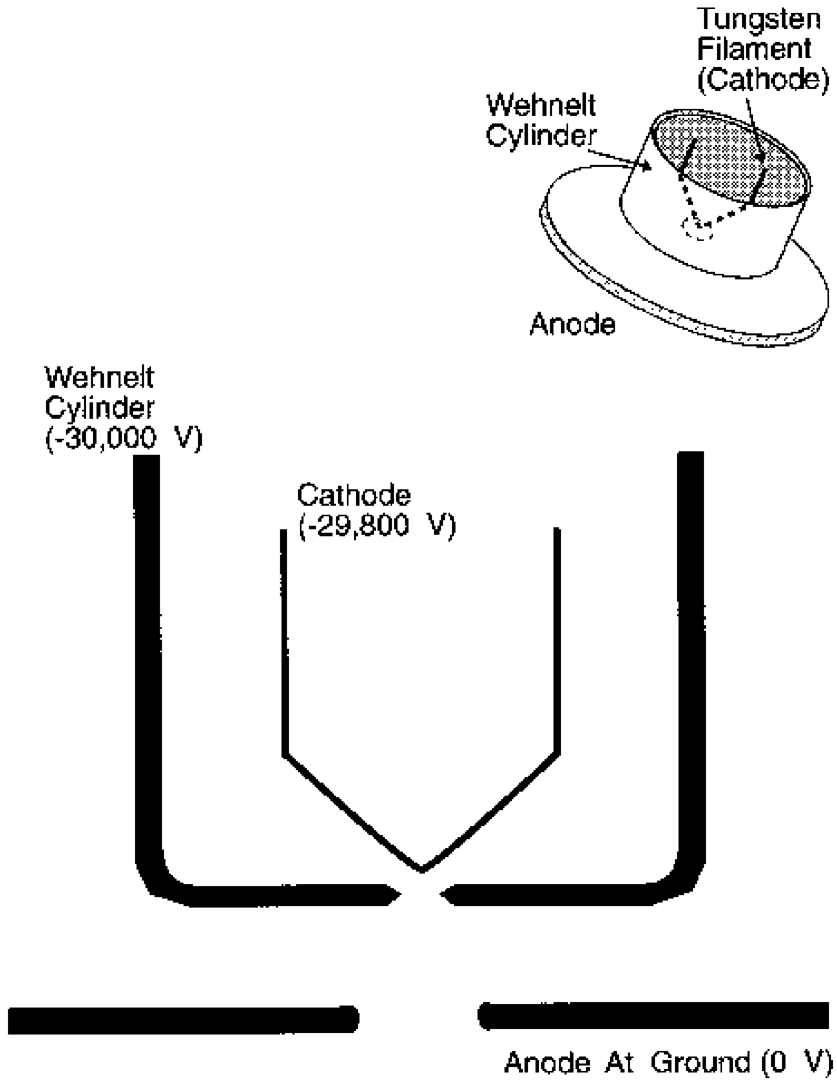
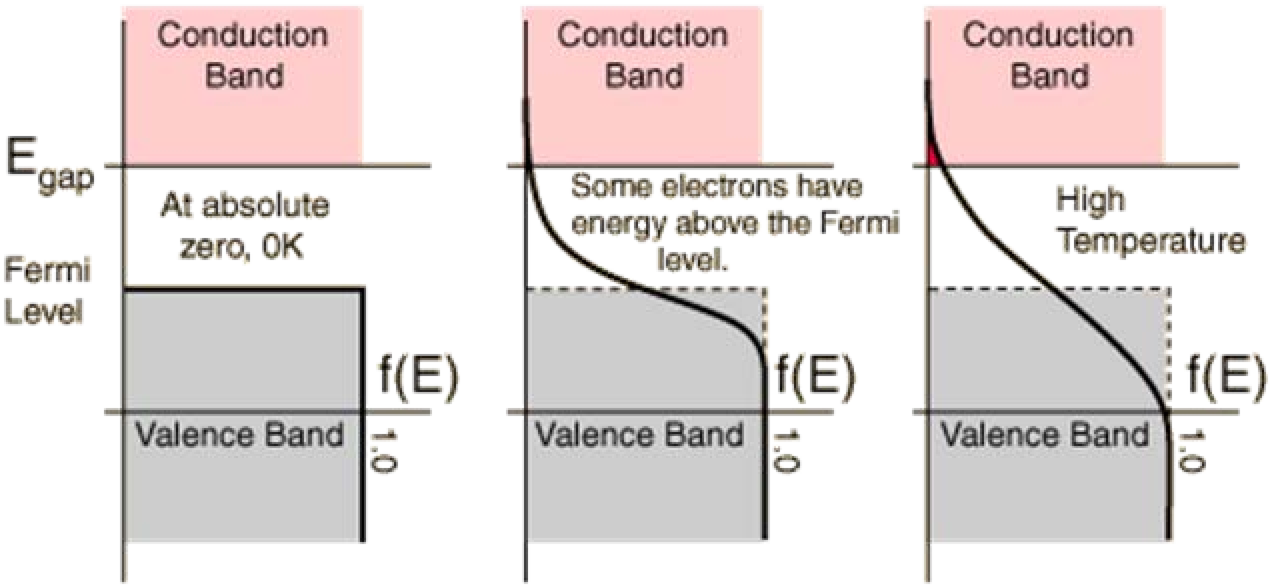


Figure 2-4 Biased electron guns, showing the position of the cathode, Wehnelt cylinder, and anode.

Thermal emission



No electrons can be above the valence band at 0K, since none have energy above the Fermi level and there are no available energy states in the band gap.

At high temperatures, some electrons can reach the conduction band and contribute to electric current.

$$f(E) = \frac{1}{\exp\frac{(E-E_f)}{kT}+1} \approx \exp\frac{(E-E_f)}{kT}$$

Operation of the Self-biased Gun

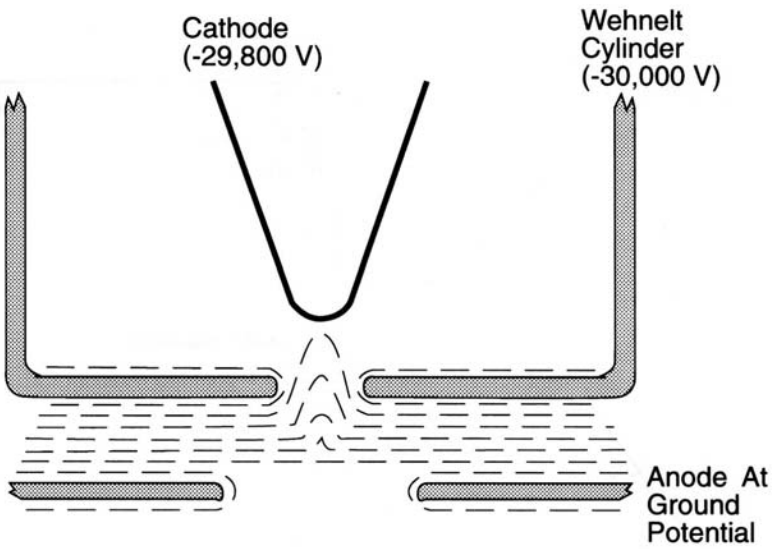
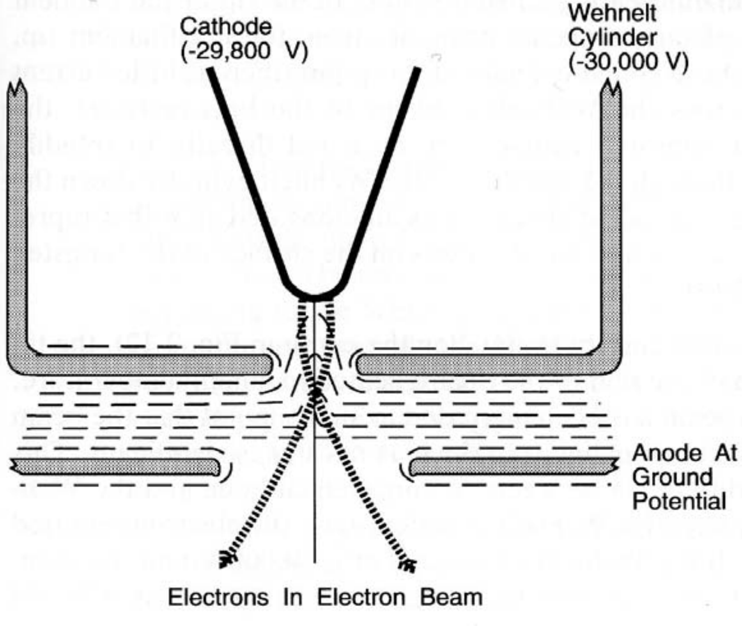


Figure 2-10 Equipotential lines of electrostatic force in a biased gun.

Figure 2-11 Path of the be
electrons in a self-biased gu



열전자 방출 전자총

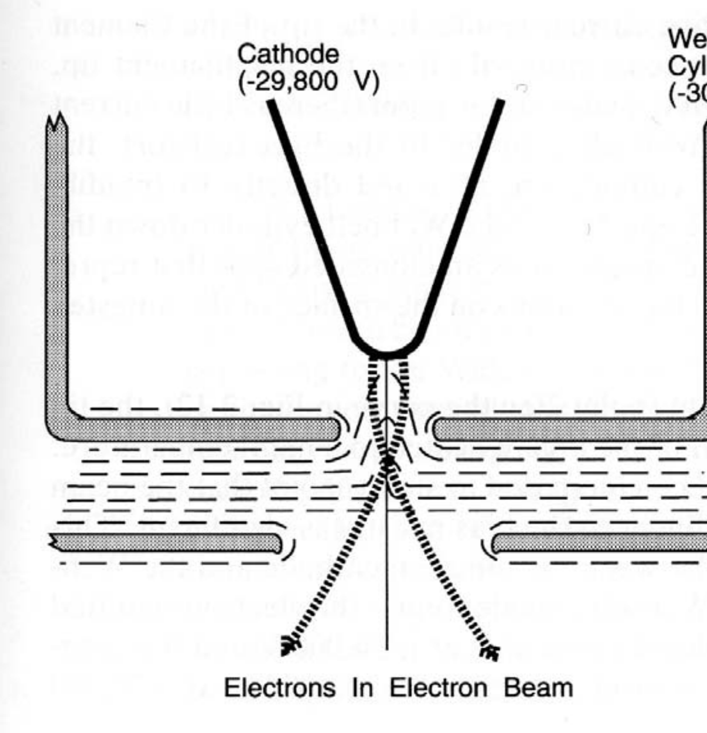


Figure 2-11 Path of the be electrons in a self-biased gu

Cathode(Filament): 열전자 방출**(W, LaB_6)**

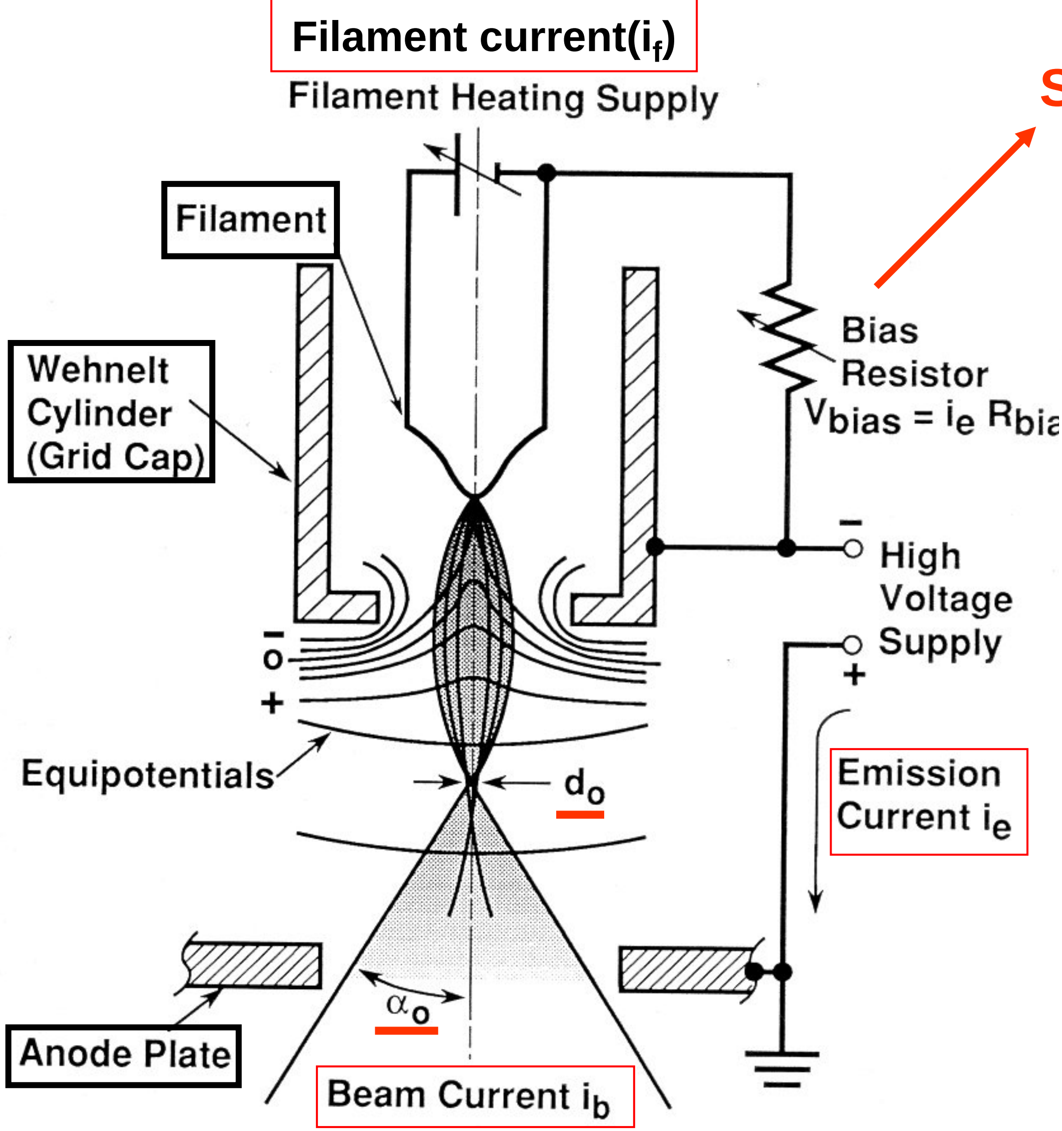
Wehnelt: 열전자 집속**, 1~3 mm** 직경의 **aperture (hole)**

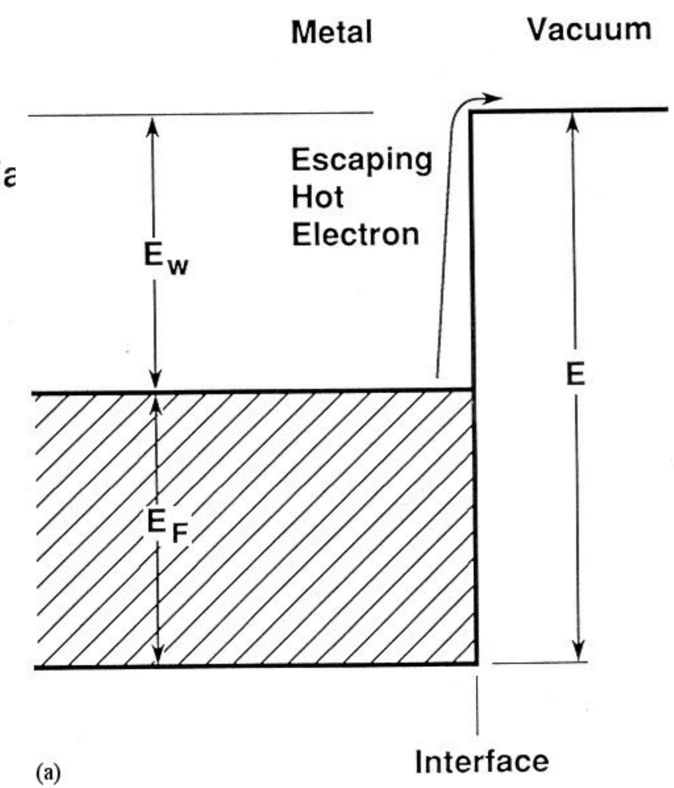
Anode: 열전자 가속

가속전압**(Accelerating Voltage): cathode**와 **Anode** 사이의 **potential** 차이

- 보통 **30,000V (30kV)**

Self Biased Electron Gun





Richardson's law work function

$$J = A_C T^2 \exp(-E_W / kT)$$: 방출 전자 전류밀도 **(A/cm²)**

♦ **Brightness : concept of current density**

$$\beta = \frac{\text{current}}{area \times solid\ angle} = \frac{4i_b}{\pi^2 d^2 \alpha^2} \ \text{A/cm}^2\text{sr}$$

Brightness $\uparrow \Rightarrow$ current $\uparrow$ in same beam size

$\Rightarrow$ beam diameter $\downarrow$ in same current

Maximum theoretical Brightness (Langmuir eq'n)

$$\beta_{\max} = \frac{J_c e V_o}{\pi k T} \ \text{A/cm}^2\text{sr for thermionic gun} \sim 9.2 \times 10^4 \text{A/cm}^2\text{sr}$$

$$\beta_{\max} = \frac{J_c e V_o}{\pi \Delta E} \ \text{A/cm}^2\text{sr for field emission gun}$$

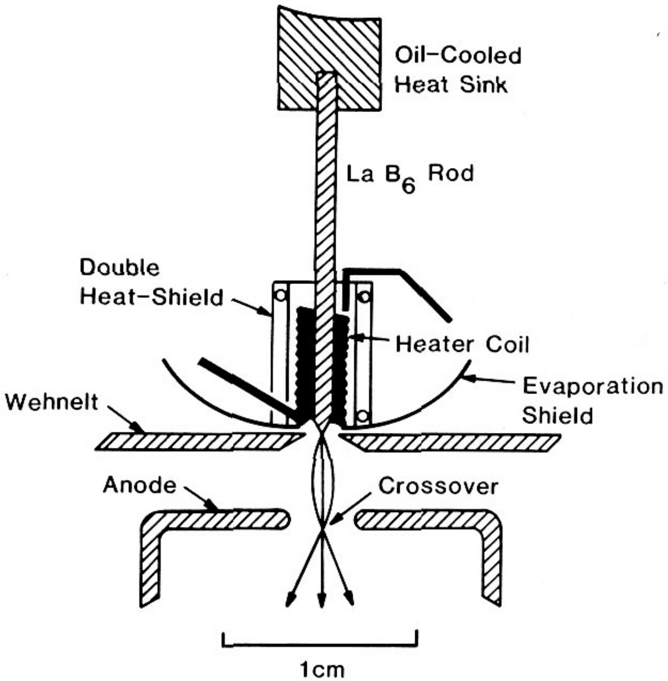
$\rightarrow \Delta E$ 0.3eV for cold emission

$\beta_{\max} \sim 2 \times 10^9 \text{A/cm}^2\text{sr}$

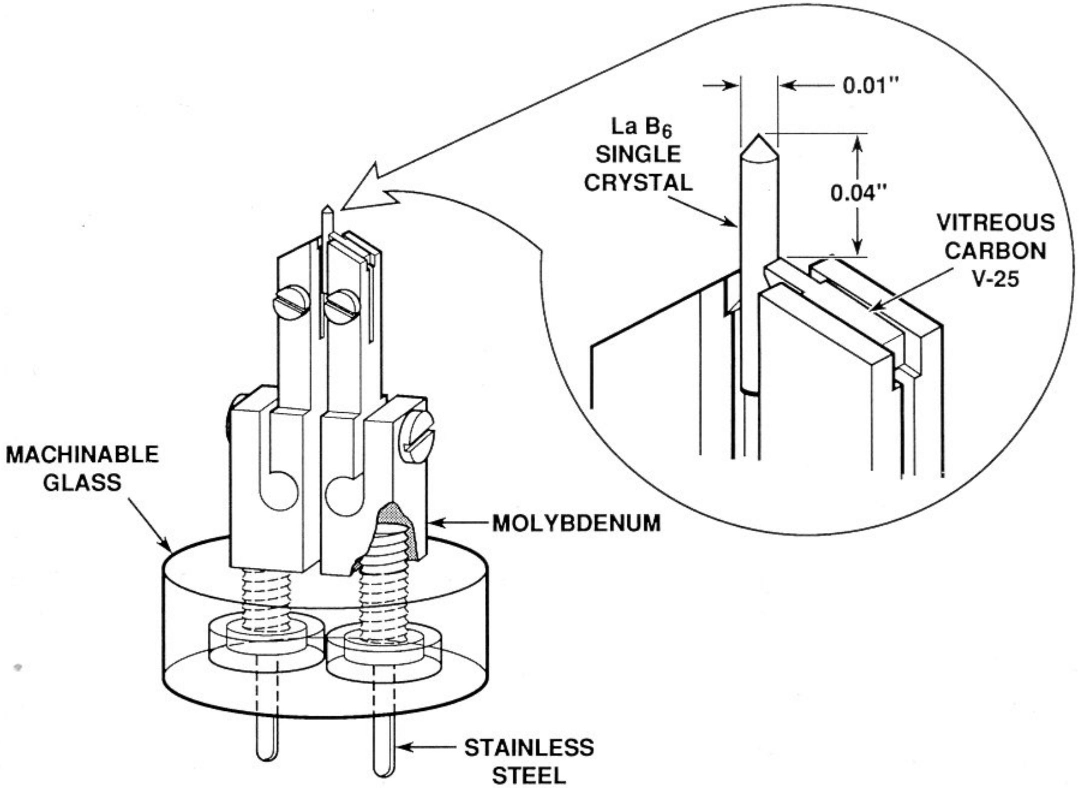
2. LaB_6 Electron Gun

High brightness(5-10times) : lower work function(2.5eV : 4.5eV for W), expensive but longer lifetime(1000hr), high vacuum(10^{-7}torr)

$$\beta_{max} = 10^5 \ \mathbf{A/cm^2 sr}$$



간접 가열 방식



직접 가열 방식

Heating current of LaB_6 filament