真空技術在SEM, FIB之應用

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Outline

- 真空技術基本概論
- 真空系統
- 真空幫浦
- 真空量測與真空計
- 真空材料
- 真空系統應用(SEM, FIB)

真空技術基本概論

真空的定義

- 絕對真空 ：即空無一物所謂真的空，也可稱為理想真空
- 相對真空 :一般所指的真空係表示某一特定空間內的氣體壓力小於一大氣壓
- 自然真空 :指存在於自然界的真空如外太空.月球表面
- 人造真空 :指以人為力量，如利用抽氣幫浦將某一特定空間內的氣體排出,而達到相對真空者

什麼是真空技術？

創造小於一大氣壓(<1 atm)的科學技術

- Vacuum is NOT a “sucking” process.
- A molecule is only removed from a chamber when it enters the pump via random collisions.

真空單位

- Atomspheres (atm) : 1 atm= 760 mmHg = 760 Torr
- Torr, mmHg: Most commonly used pressure unit, based on mercury vacuum gauges. (舊真空單位) 1 Torr = 1 mmHg = 1/760 atm
- Pascal (Pa): SI unit (國際真空壓力單位) 1 Pa = 1 N/m^2 = 0.01 mbar
- mbar : 現行真空壓力 1 mbar= ¾ Torr = 100 Pa

	mbar	Pa	Torr	atm
mbar	1	100	0.75	9.87×10^{-4}
Pa	1×10^{-2}	1	7.5×10^{-3}	9.87×10^{-6}
Torr	1.33	133	1	1.32×10^{-3}
atm	1013	101325	760	1

Degree of Vacuum

- Atmospheric: 760 Torr
- Low Vacuum: 1 to 1×10^{-3} Torr

- Medium Vacuum: 1×10^{-3} to 1×10^{-5} Torr
- High Vacuum (HV): 1×10^{-5} to 1×10^{-8} Torr

- Ultra-High Vacuum (UHV): < 1×10^{-8} Torr

Degree of Vacuum

Degree of Vacuum	Pressure (Torr)	Gas Density, ρ (molecules m^{-3})	Mean Free Path (m)
Atmospheric	760	2×10^{25}	7×10^{-8}
Low	1	3×10^{22}	5×10^{-5}
Medium	10^{-3}	3×10^{19}	5×10^{-2}
High	10^{-6}	3×10^{16}	50
UltraHigh	10^{-10}	3×10^{12}	5×10^{5}

Collision Free Conditions: $P \sim 10^{-6}$ Torr

Maintain a Clean Surface: $P \sim 10^{-10}$ Torr

Mean Free Path

Mean Free Path (平均自由徑) :

$$\lambda = \frac{k_B T}{\sqrt{2}\pi d^2 P} \xrightarrow{300K} \frac{5}{P(mtorr)} cm$$

d - molecule diameter

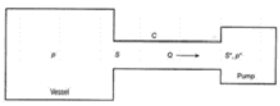
P= 10^{-3} torr,	λ	~ 5 cm
10^{-6} torr,		~ 50 m
10^{-10} torr,		~ 500 km

不同真空之氣流狀態

Viscous flow(黏滯流) :

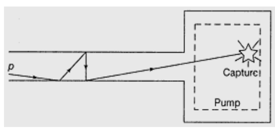
λ << d or d/λ >100

d: pipeline diameter



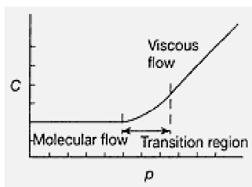
Molecular flow (分子流):

λ >> d or d/λ < 2



Transitional flow (過渡流):

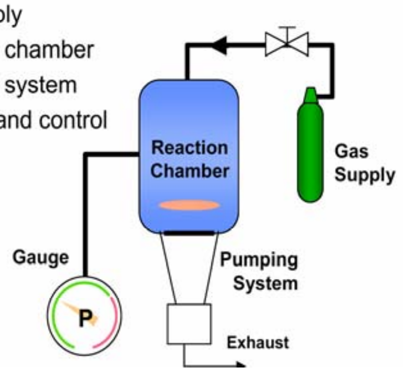
2< d/λ ≦100



真空系統

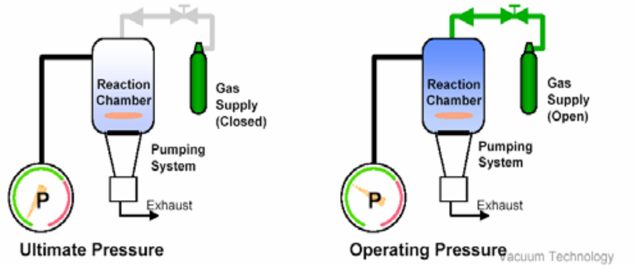
真空系統之基本組成

- A typical vacuum system is made of four parts
  1) Gas supply
  2) Reaction chamber
  3) Pumping system
  4) Gauges and control



ultimate pressure & operating pressure

- At first the gas supply is shut off and the chamber is evacuated till the **ultimate pressure** is reached.
- Then the gas supply is opened and the pressure rises to the **operating pressure**. The process occurs at the operating pressure.



Vacuum Pump

Conductance

Conductance(氣導) C: 氣體通過管路或孔徑的容易性。
Unit : liter/s

Gas flow (Throughput)氣體流量: Q
壓力P1及P2的真空容器，其間用管路或單純的孔連接，通過此處的氣體流量Q爲：

Q=C(P1-P2)

Conductance of a Straight Tube

Viscous flow

$$C \approx \frac{\pi}{128}\frac{D^4}{\eta L}\frac{P_1+P_2}{2} \xrightarrow{\text{air @ RT}} C(liter/\sec) \approx 10\frac{[D(cm)]^4}{L(cm)}$$

Molecular flow

$$C \approx \frac{1}{6}\sqrt{\frac{2\pi k_B T}{M}}\frac{D^3}{L} \xrightarrow{\text{air @ RT}} C(liter/\sec) \approx 10\frac{[D(cm)]^3}{L(cm)}$$

Maximize D, minimize L, avoid bending

Pump Speed

Intrinsic pumping speed S_P (liter/sec, cfm)

$$Q = P_{inlet}\, S_P$$

Effective pumping speed S_{eff}

$$\frac{1}{S_{eff}} = \frac{1}{S_P} + \frac{1}{C}$$

Proper selection of pipeline width, avoid limiting S_p

Pumping down

$$S_{eff}P - Q = -V\frac{dP}{dt} \longrightarrow P = P_o e^{-\frac{S_{eff}t}{V}} + \frac{Q}{S_{eff}}$$

Early Stage

$$P = P_o e^{-\frac{S_{eff}t}{V}}$$

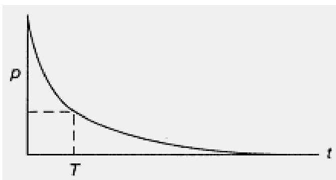
Ultimate

$$P_{ultimate} \approx \frac{Q}{S_{eff}}$$

計算所需抽氣時間

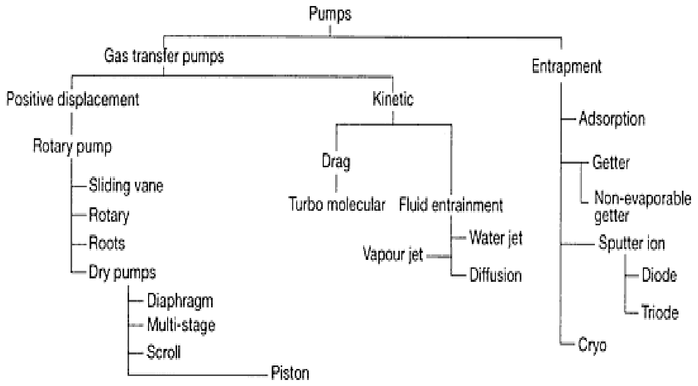
- 計算抽氣速度

$$t = \frac{V}{S}\ln\frac{p_0}{p}$$



- Example: if 真空室体積V = 40升； 氣導 S = 0.5 l s^{-1} then the time taken for the pressure to fall from p_0 = 1000 mbar to 1 mbar is:
- Answer:
  t = (40/0.5)1n(10^3) = 80x2.3log10^3 = 80 x2.3x3 = 552 s ~ 9 min

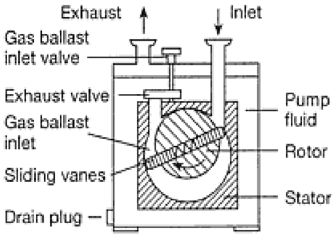
Pump 分類



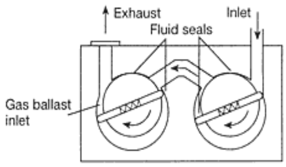
Pump 種類

- **Ultimate Pressure**
  - Low Vacuum (Rough) Pumps
    - Rotary Vane Pumps
    - Sorption Pumps
  - High Vacuum Pumps
    - Diffusion Pumps
    - Turbo Molecular Pumps
  - Ultra-High Vacuum
    - Turbo Molecular Pumps
    - Ion Pumps
    - Titanium Sublimation Pumps
- **Oil / Oil-Free**
  - Oil
    - Rotary Vane Pumps
    - Diffusion Pumps
    - Turbo Molecular Pumps
  - Oil-Free
    - Turbo Molecular Pumps
    - Ion Pumps
    - Titanium Sublimation Pumps

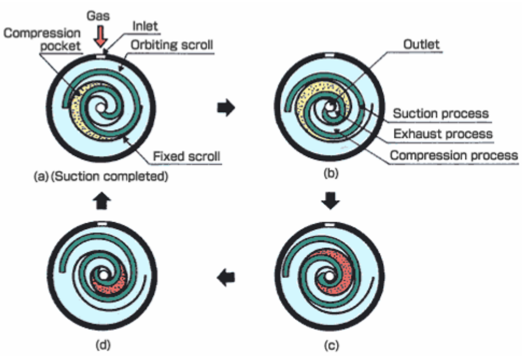
Rotary Vane Pump



- Atmosphere to 10^{-3} torr
- Robust, inexpensive
- Oil lubricated

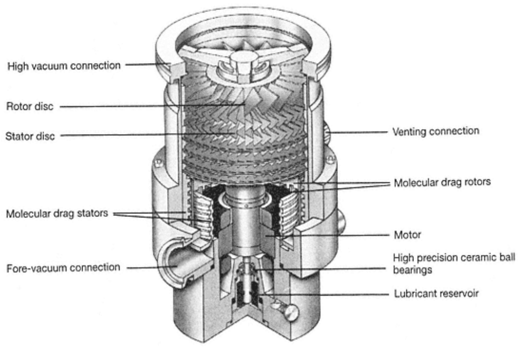


Dry scroll pump

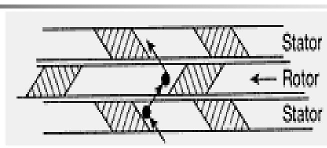


- Atmosphere to 10^{-2} torr
- low noise
- Oil-free

Turbo Molecular Pump



工作原理



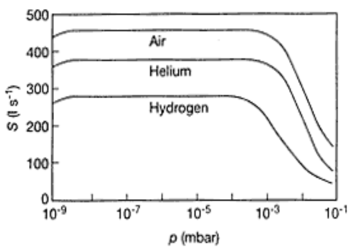
- Molecules mechanically pumped by collision with angled high speed turbine blades (rotor).
- Several rotor arranged in a series spinning at 30,000-60,000 rpm.
- Rotor tangential velocity is on the order of the average thermal velocity of molecules.
- Atmosphere to 10^{-10} Torr
- Oil/grease/electromagnetic bearings
- Most common HV/UHV pump.

渦輪幫浦之優缺點

- **Advantage**
  - Correctly operated they do not back-stream oil into the vacuum system at any time.
  - They can be started and stopped in a few minutes.
- **Disadvantage**
  - Turbo pump can be noisy and they induce vibration.
  - Turbo pumps are expensive.

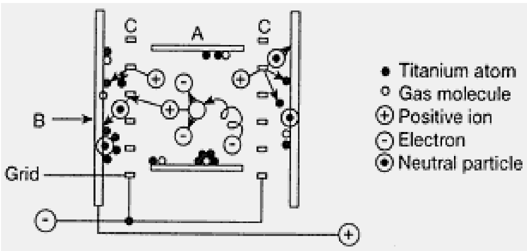
使用渦輪幫浦之注意事項

- When turbo pumps are used with corrosive or abrasive gas mixtures or those having a high O_2 content (25%), a dry nitrogen purge should be used through the purge ports provided.
- Where low vibration levels are required (e.g. electron microscopes) the use of all-magnetic bearings is recommended.



離子幫浦 Ion Pump

- High voltage between anode and cathode (~5 kV)
- Gas molecules are ionized by collisions with electrons and are accelerated to cathode.
- Sputtered Ti atoms act as "getter" for reactive gases.
- 10^{-4} Torr to 10^{-11} Torr

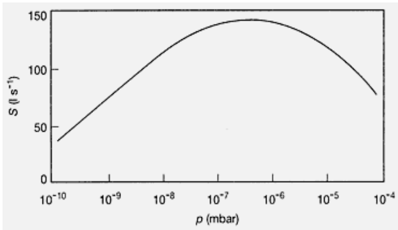


離子幫浦之優缺點

- **Advantages**
  - Clean, oil-free.
  - No moving parts, no vibrations, quiet.
  - Low power consumption and relatively long operating lives.
- **Disadvantage**
  - Do not pump noble gases well.
  - Requires "regeneration" of Ti
  - every 4-6 years.
-

使用離子幫浦之注意事項

- The life of a typical diode pump is 40’000 h at 10^{-6} mbar and proportionally longer at lower pressures.
- It is not a suitable pump where cyclic operations require it to be continually brought to atmospheric pressure.



Vacuum Gauges

Vacuum Measurements

Mechanical Gauges

Mechanical movement of a surface (diaphragm)

Independent of gas properties

P> 10^{-5} torr

Gas Property Gauges

Bulk property, e.g., thermal conductivity, viscosity

Dependent on gas composition

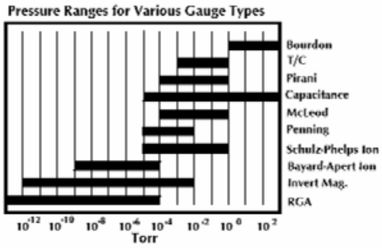
$10^{2} – 10^{-4}$ torr

Ionization Gauges

Charge collection

Dependent on gas composition

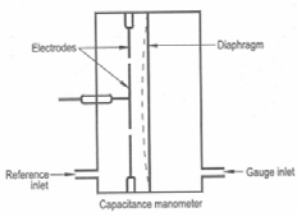
$10^{-4} – 10^{-10}$ torr



Mechanical gauge

- 利用隔膜因壓差產生位移而改變電容
- 常用於 PECVD、濺鍍等半導體製程設備

Capacitance Manometer



P_{max}: 10^{4} ~ 10^{-1} torr

Dynamic range: ~ 10^{4} below max

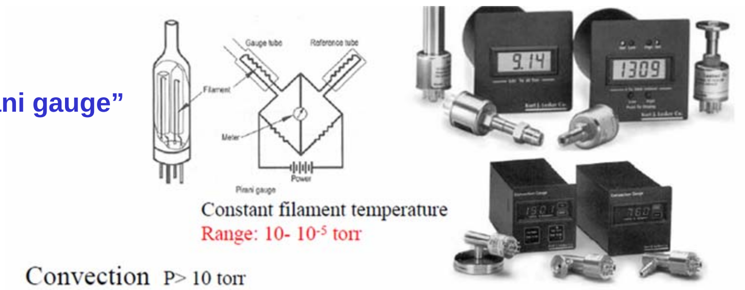
Accuracy: 0.25% - 0.08%.

Sensitive to temperature variations at gauge head: often maintained > RT

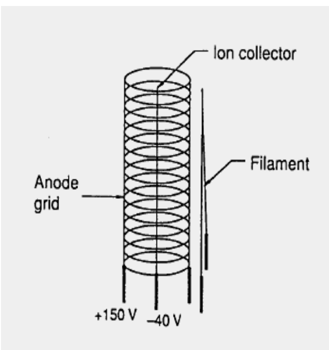
Gas Property gauge

- Two identical heated filaments; one sealed at HV, one exposed to system.
- Current flows through Wheatstone bridge circuit.
- Pressure difference indicated by meter (non-linear).
- Simple, reliable, inexpensive.

"Pirani gauge"

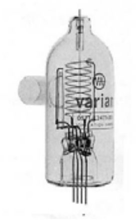


Ionization Gauge



- Heated filament produces electrons via thermionic emission.
- Electrons are accelerated towards anode grid.
- Many electrons pass through the grid and create positive ions from collisions with gas molecules.
- Ions are accelerated to collector wire.
- Measure the current between anode and collector.
- Operate at 10^{-4} to 10^{-11} Torr
- Sensitive, high accuracy, widely used.

Ionization Gauge

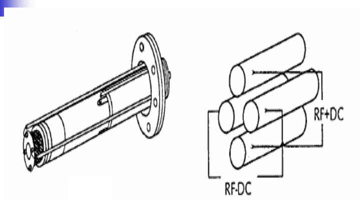


VARIAN 571

INFICON Compact Process Ion Gauge IMR

- 優點
  - very reliable
  - straightforward to operate
  - easily be de-gassed by electron bombardment
- 缺點
  - hot filament that can 'burn out' due to accidental exposure to atmospheric air (sol. two switchable filaments)
  - significant ionic and electrical pumping effects which produce a lower pressure in the gauge (sol. gauge is used 'nude')

Quadrupole Residual Gas Analyzer



Mass Spectrometer

HORIBA STEC RGA Micropole™ System

- Quadrupole mass spectrometer - RGA (residual gas analyzer)
- 10^{-4} to $<10^{-14}$ torr
- Total pressure mode integrates all ion intensities
- Partial pressure mode indicates residual vacuum composition
- Highly accurate, precise
- Complex, expensive.

Vacuum Materials

真空材料

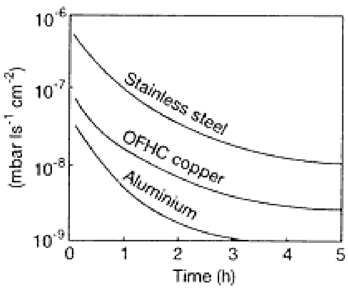
- 真空材料與零件設計與選用主要決定於真空製程之特性與真空度需求。
- 欲使半導體製程之真空系統獲得最佳性能與成本，真空材料與零件的選用是非常重要的因素。
- 真空材料與管件選用要求
  - 維持真空度
  - 不污染製程
  - 於環境與人體無害

特性需求

- 可加工性
- 在操作溫度與壓力下保持強度
- 熱性質
  熱膨脹須與接鄰材料接近 (例如：超高真空系統flange須承受烘烤)
- 氣體負荷
  材料須不透氣（不具孔隙或裂縫）
  前處理後材料釋氣量要小（表面不易吸附）
- 反應
  真空材料不與系統其他材料或製程物質反應
- 幅射
  材料暴露在幅射線下（如neutrons, x-rays 或 高能粒子 ）不會放出氣體或劣化，例如：密封彈性體(elastomer)硬化、觀察窗變黑。

真空常用材料-金屬

- 奧斯田不銹鋼
  - 材料代號EN58A, EN58B(US321), EN58E(304) 最常用於氬焊腔體
  - 材料代號EN58B用於低導磁需求
  - 釋氣率低
  - 材料代號EN58F(347)
  - 不適於拋光後焊接
- 中碳鋼
  - 可用於真空度低至10^{-3} mbar
  - 焊接塗佈後可用於更低壓
  - 易銹蝕



真空常用材料-金屬

- 鋁與鋁合金
  - 材料便宜、質輕運送方便
  - 耐腐蝕、 易加工與接合
  - 高溫強度差、 低含鋅量接點易蝕
  - 銅含量易導致焊接問題、 焊接後變形量大須後續加工
- 鎳合金：如Inconel, Kovar
  - 高溫下高強度
  - 極佳抗腐蝕性
  - 不易取得、價格高、 加工困難

真空常用材料-金屬

- 鈦（Titanium）
  - 真空中清潔度高、重量輕、延性佳
  - 例：常用其捕氣性於ion pump cathodes和getter pump filaments.
- 銅（Copper）
  - 含氧量低、氧氣流傳導性高 (OFHC)
  - 容易加工、抗腐蝕
  - 氫氣氛下硬焊不易
- 黃銅（Brass）：Cu-15~20%Zn
  - 適用於特殊應用、材料等級多、抗腐蝕
  - 100℃以上操作有鋅蒸氣的問題、小心鑄孔

真空常用材料-陶瓷與玻璃

- 陶瓷(Ceramics)
  - 對於使用溫度可達1500℃的真空元件是最適合的材料
  - 使用時需戴無綿質手套防止括痕與碰撞（脆性）
  - 可以硬焊法與金屬接合獲得複合材料元件
  - 加工不易
- 玻璃(Glass)
  - 廣汎用於真空腔體、元件與管路
  - 最常用玻璃爲硼玻璃(borosilicate glass, 如 Pyrex)
  - 可用於觀察窗(View port)、鉛玻璃可阻隔X光
  - 抗腐蝕性佳

真空常用材料-塑膠

- 塑膠（Plastics）
  與金屬相較，通常塑膠易吸氣、易透氣，使用需小心
  - PTFE
    - 低釋氣率、電絕緣佳、使用溫度較高之塑膠、具自潤滑效果
    - Glass-filled PTFE：使強度提高、透氣量降低
  - Polycarbonate.
    - 中釋氣率與吸水性、電絕緣佳
  - Nylon and Acrylic
    - 高釋氣率與吸水性、具自潤滑效果
  - PVC
    - 高釋氣率與吸水性、可撓性、 用於暫時性管路(如：測漏).
  - Polyethylene
    - 完全釋氣後才可用
  - Synthetic Resins
    - 不建議使用

Scanning Electron Microscope (SEM)

History

1590 first microscope

17 century first OM

1932 Ernst Ruska and Max Knoll, first TEM

- EM were developed due to the limitations of Light Microscopes (500x or 1000x)

1938 von Ardenne, first STEM

- Adding scan coils to a TEM

1942 V. Zworykin, J. Hillier and G. Snyder, first SEM

- Secondary- electron emission would be responsible for topographic contrast (resolution ~ 1 μm)

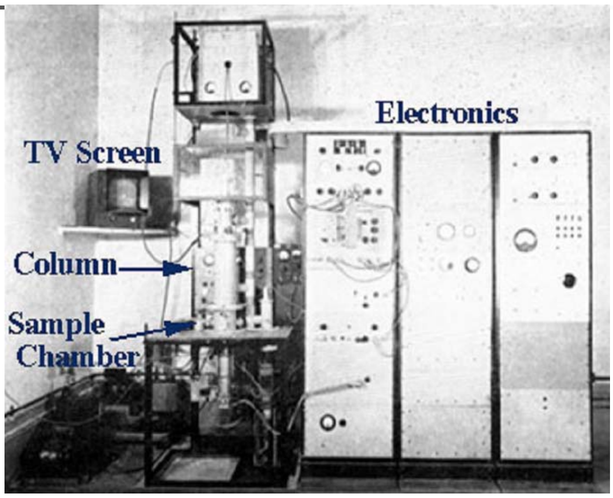
1956 K. C. A. Smith

- Replaced electrostatic with electromagnetic lenses and first insert a stigmator into the SEM

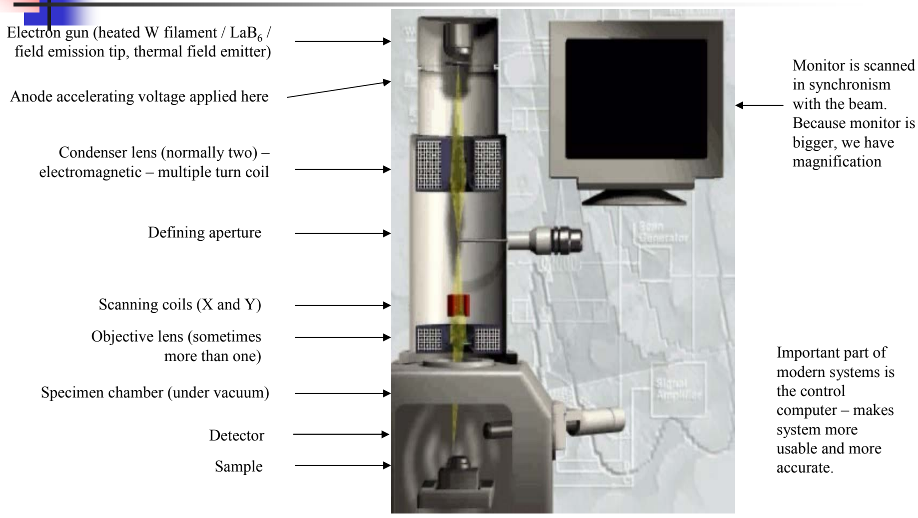
1964 First commercial instruments by Cambridge Scientific Instrument Co.

- With three magnetic lenses and the gun using the E-T detector.

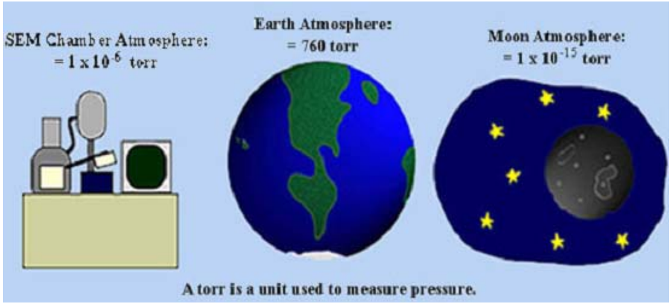
First modern SEM



SEM Principle



Why SEM need Vacuum ?



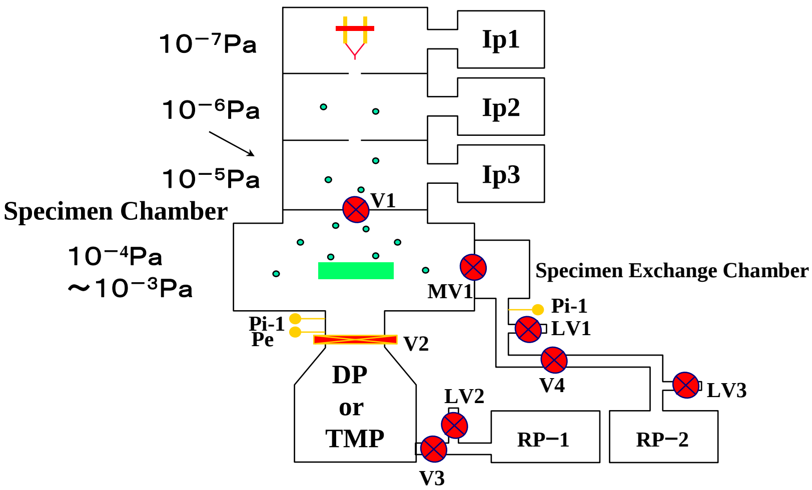
When a SEM is used, the column and sample must always be at vacuum.

•If the filament were surrounded by air, it would quickly burn out.

•If the column were full of air, the electrons would collide with the gas molecules and never reach the sample.

This can lower the quality of the image.

Vacuum System of SEM



Why use SEM?

An electron microscope use a focused beam of

electrons instead of light to “image” the specimen and gain information as to its structure and composition.

De Broglie: particles can also behave as waves.

$$\lambda_e = \frac{h}{mv} = \frac{1.22}{\sqrt{V}}\ (\text{nm})$$

v : velocity of electron
m: mass of electron
h : Planck’s constant, 6.63 x 10^{-34} (J-sec)

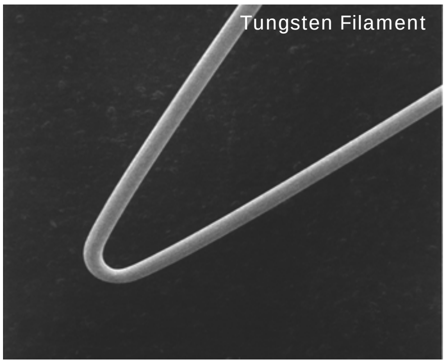
At 10 kV => λ = 0.12 Å

visible light 4000~7000 Å → ***Gain better resolution***

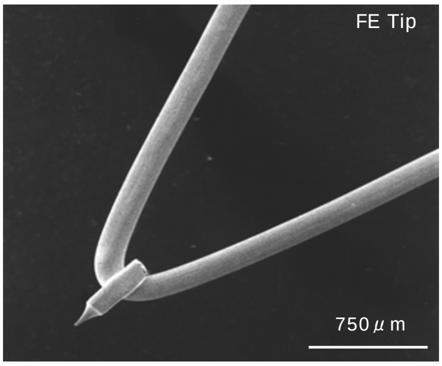
SEM structure

- Electron gun – 2 type
- Condenser lens - 3 type aberrations
- Condenser aperture - aberration
- Scanning coil – Mag.
- Stigmator – improve astigmatism aberration
- Objective lens – focus

Electron Gun

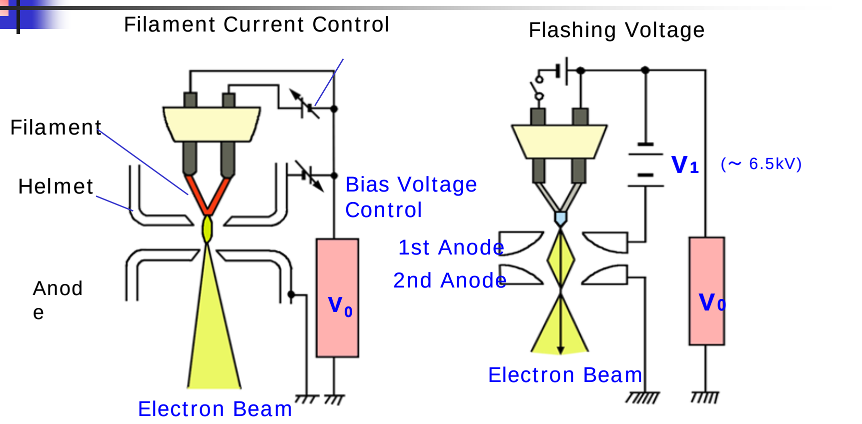


熱游離式
(Thermionic Emission)



場發射式
(Field Emission)

Electron Gun



Thermionic Emission

Cold Field Emission

V_0: Accelerating voltage

V_1: Extraction voltage

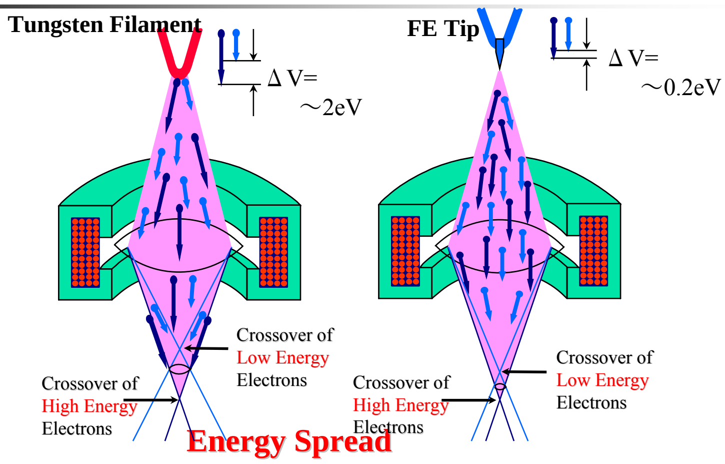
Electron Gun

The purpose of the electron gun is to provide a large, stable current in a small electron beam.

	Type	相對於鎢燈絲的亮度	加熱溫度(K)	電子槍的尺寸	電子能量散佈(eV)	使用壽命(hr)	是否需flashing	真空度要求(Pa)
熱游離式 (Thermionic Emission)	Tungsten Wire	1	2700	50μm	1-3	40-100	No	10^{-5}
	LaB_6	30	1800	1μm	1-2	200-1000	No	10^{-7}
場發射式 (Field Emission)	Cold	500	R.T.	5 nm	0.3	>1000	Yes	10^{-10}
	Thermal	500	1800	5 nm	1.0	>1000	No	10^{-9}
	Schottky	500	1800	15-30 nm	0.3-1.0	>1000	No	10^{-8} ~ 10^{-9}

Thermionic emission occurs when enough heat is supplied to emitter so that electrons can overcome the work-function energy barrier E_w of the material and escape from the work function.

Electron Gun

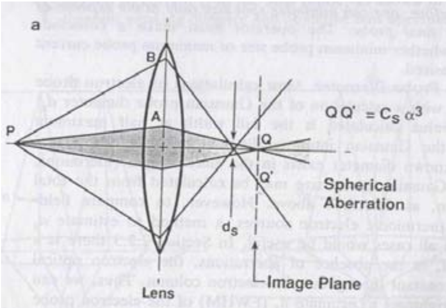


Energy Spread

Effect of chromatic aberration

Lens aberrations

1. Spherical aberration - imperfect lens



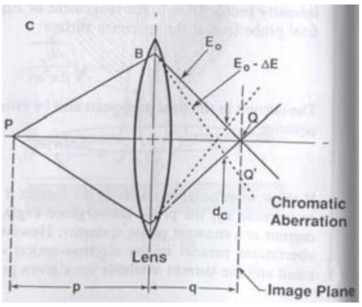
$d_s = 0.5 C_s \alpha^3$

Cs : spherical aberration coefficient

α : beam divergence

Lens aberrations

2. Chromatic aberration – energy spread in electron beams



$d_c = C_c(\triangle E / E)\alpha$

C_c : chromatic aberration coefficient

α: beam divergence

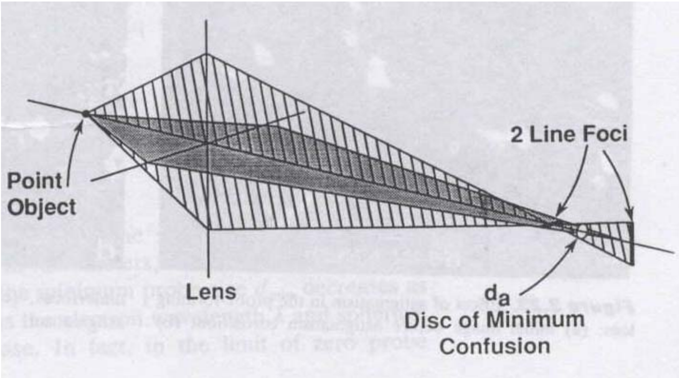
E : incident beam energy

$\triangle$E : energy spread of the beam

The higher of electron energy , the smaller of d_c

Lens aberrations

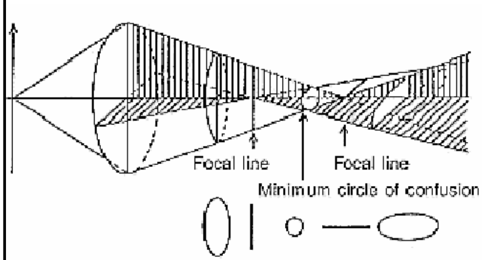
3. Astigmatism – asymmetry in the focusing field



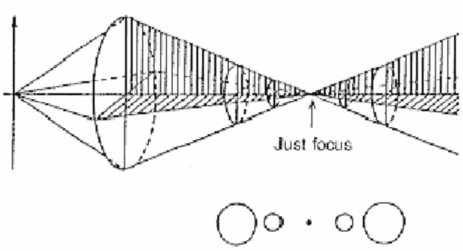
Astigmatism can be corrected with the stigmator, a device that applies a weak supplemental magnetic field to make the lens appear symmetrical to electron beam.

Lens aberrations

4. Astigmatism



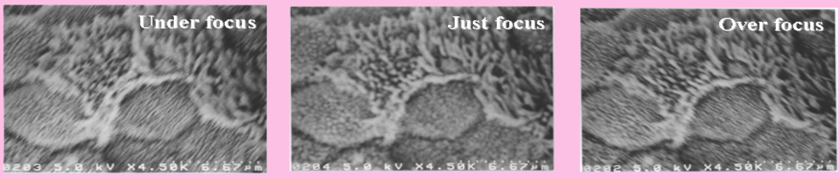
Shape changes in electron beam when there is astigmatism

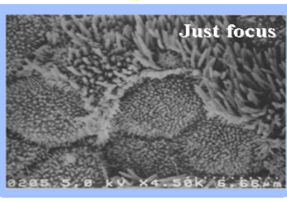


Shape changes in electron beam when astigmatism is corrected

Lens aberrations

there is astigmatism

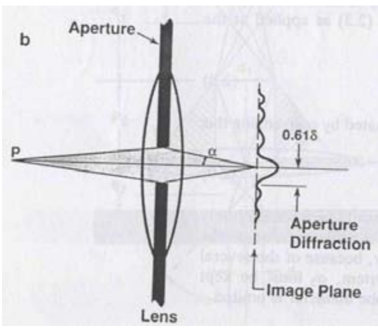




astigmatism is corrected

Lens aberrations

2. Aperture diffraction – Fraunhofer diffraction at the aperture



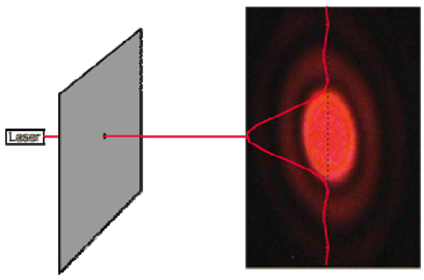
$d_d = 0.61\lambda / \alpha$

where $\lambda = 1.226/(V)^{1/2}$

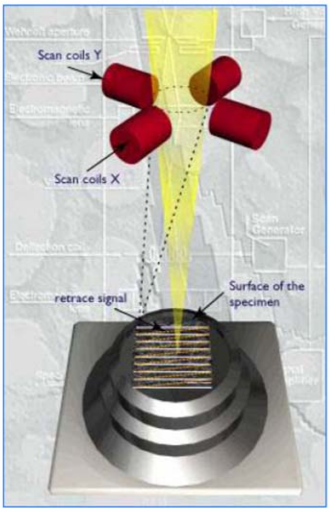
λ: wavelength of electron(nm)

α : beam divergence

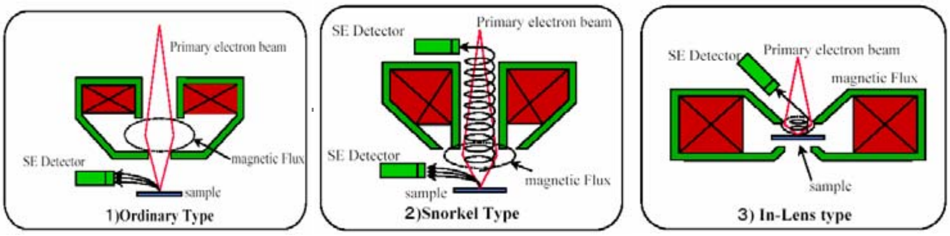
V : accelerating voltage(volt)

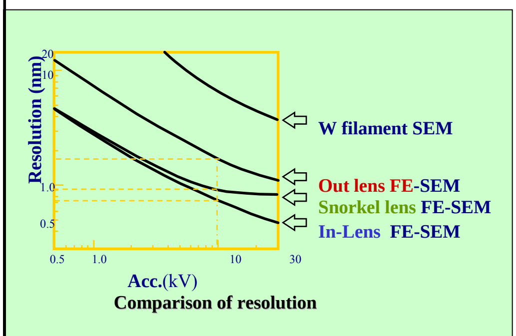


Scanning coil



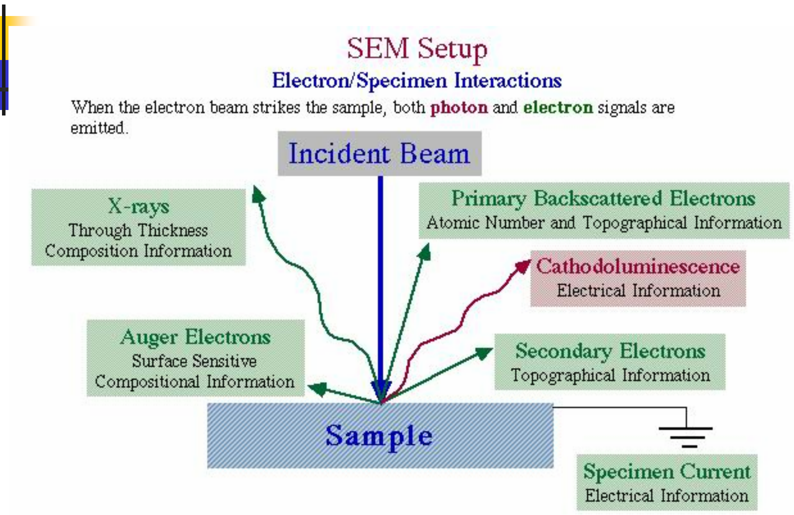
Objective Lens





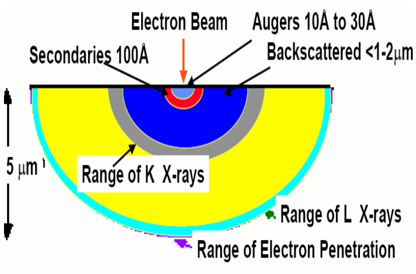
Resolution: In-lens > Snorkel > Ordinary
(judge by spot size)

Electron-specimen interactions



The primary electron beam-specimen interaction in the SEM. The signals most commonly used are the Secondary Electrons, the Backscattered Electrons and X-rays.

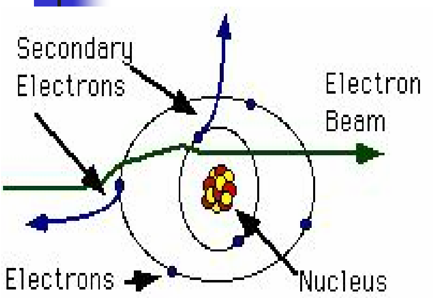
Electron Beam / Specimen Interactions



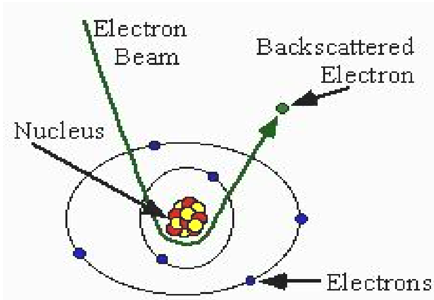
Auger e⁻	low energy, at surface, results from inner shell displacement
Secondary e⁻	low energy, mostly close to surface
Backscattered e⁻	high energy, deeper in sample
X-ray photons	deepest in sample
Absorbed e⁻	measure of conduction of electrons through sample
Cathodelumine scence	interactions causes sample to glow

Specimen with atomic number : 28 , Vacc : 20kV

Electron-specimen interactions

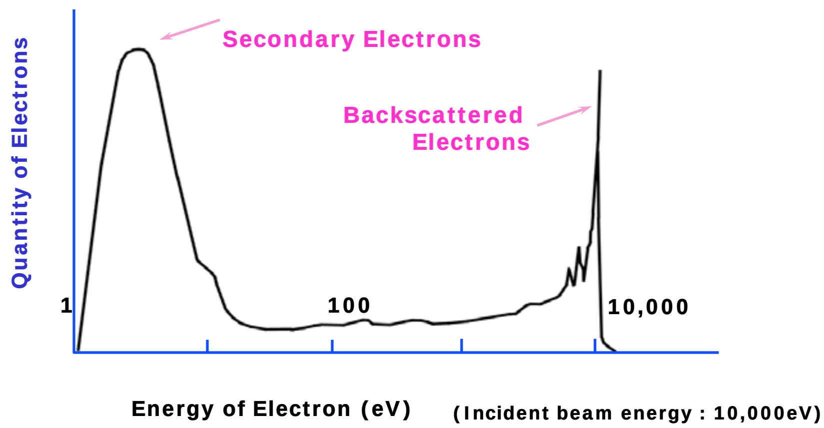


Secondary Electron



Backscattered Electron

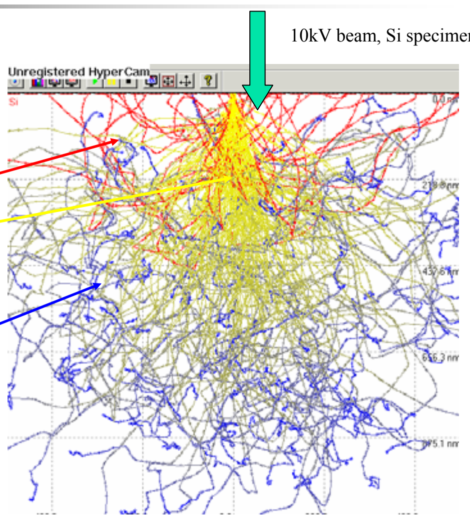
Energy spectrum of the electrons



Energy spectrum of the electrons

Specimen interaction (MonteCarlo Simulation)

10kV beam, Si specimen



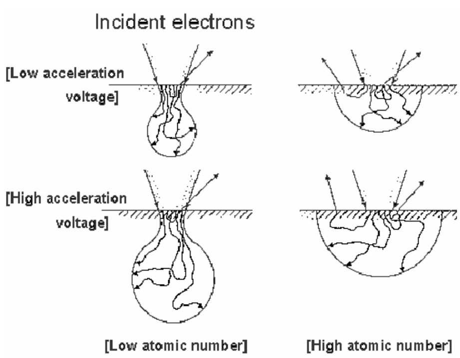
Electrons undergo elastic (nuclear) scattering, and inelastic scattering leading to a quasi-continuous energy loss or slowing down.

Red paths are primary electrons which escape from the surface – **Backscattered electrons** (~20%). They have high energy (average about $E_b/2$)

X-rays generated here where primary electrons still have much energy

Each path generates **secondary electrons**, (which by definition have energy less than 50eV) – they escape if they are generated near the surface.

Electron-specimen interactions



High Z -> more elastic e^-, average scattering angle↑

-> easy to deviate out of the initial direction of travel more quickly

$$R = \frac{4.28 \times 10^{-6} E^{1.75}}{\rho} (cm)$$

for 20<E<20 keV

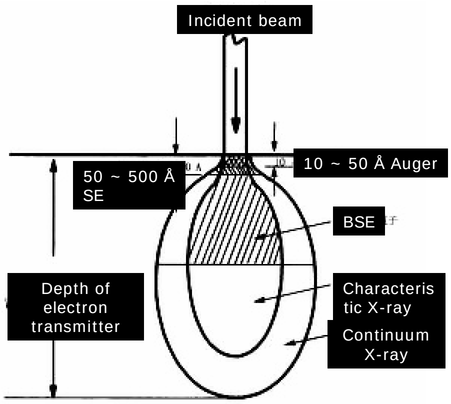
Re: penetration deep

E: acceleration voltage

P: the density of material

Electron-specimen interactions

電子束與材料作用所產生的信號範圍



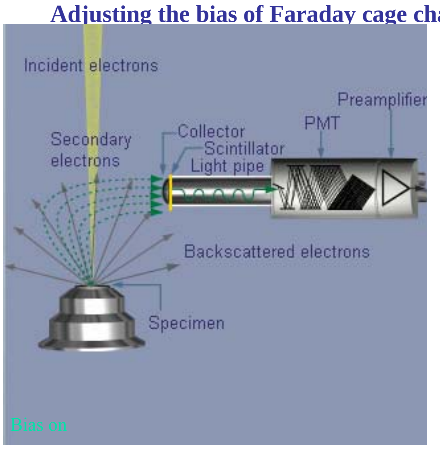
Auger e^-	low energy, at surface, results from inner shell displacement
Secondary e^-	low energy, mostly close to surface
Backscattered e^-	high energy, deeper in sample
X-ray photons	deepest in sample
Absorbed e^-	measure of conduction of electrons through sample
Cathodelumine scence	interactions causes sample to glow

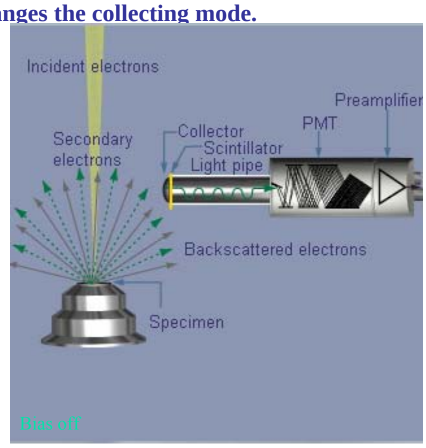
Detector

Everhart-Thornley(E-T) detector

Faraday cage – Scintillator – Light pipe – Photomultiplier tube(PMT) - Preamplifier

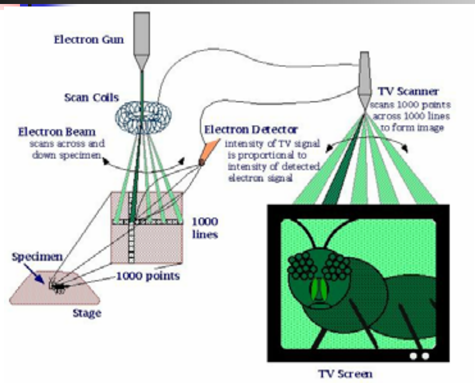
Adjusting the bias of Faraday cage changes the collecting mode.





Optimum of electron beam

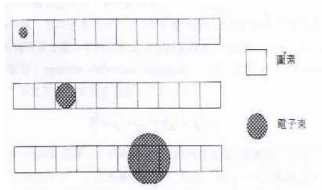
Picture element (Pixel)



10 cm length of CRT have 1000 x 1000 spot size.
So 1 spot size = 100 µm

P = 100 µm/M, M=100µm/P
P: Picture Element (pixel) Size
M: Magnification

EX:M=100kx,P=1nm
M=200kx,P=0.5nm
M=100, P=1µm

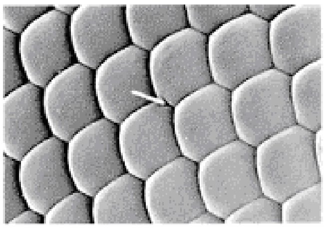


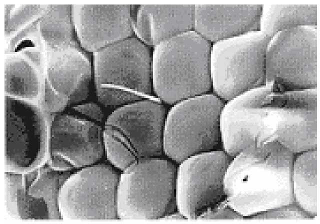
$$M = \frac{\text{Length of CRT display (L)}}{\text{Length of sample scan (l)}} = \frac{100um}{P}$$

M: Magnification

Specimen damage

1. The electron beam accelerating voltage
2. Scanning area
3. Scanning time
4. Heat conductivity of specimen



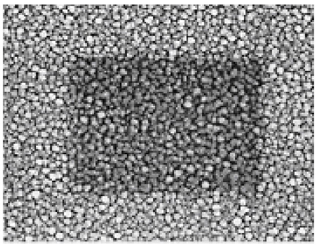


Specimen: compound eye of fly

Contamination

The conceivable residual gases in the specimen chamber, which cause contamination are:

1. From the instrument itself
2. Specimen bring into the instrument
3. Specimen itself gives off



Optimum condition of SEM operation

Depth of Focus

$$\tan \alpha = \alpha = \frac{r}{D/2}$$

$$\alpha = \frac{2r}{D} = \frac{R}{WD}$$

2r equals the pixel size of the image = P

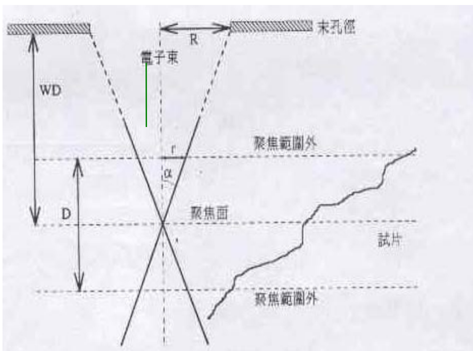
D : depth of focus

α **: beam divergence**

WD : working distance

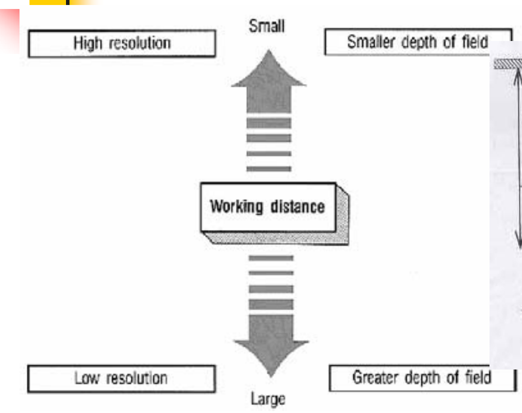
r : radius of beam

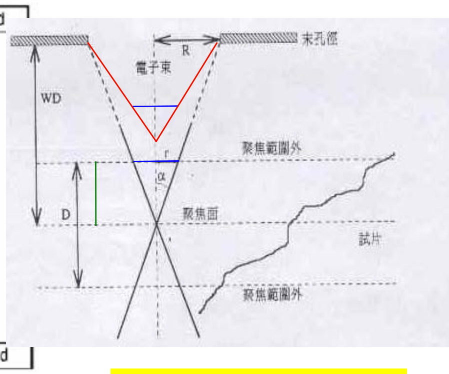
R : radius of aperture



Influence of image quality

Influence of working distance





R固定, WD↓, D↓

$$\tan\alpha = \alpha = \frac{r}{D/2}$$

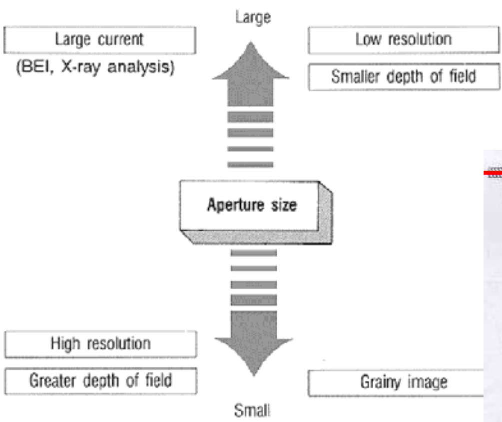
$$\alpha = \frac{2r}{D} = \frac{R}{WD}$$

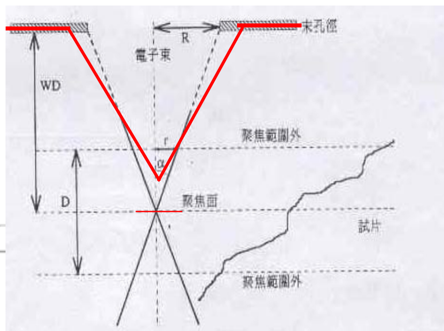
Influence of image quality

Influence of aperture size

$$\tan\alpha = \alpha = \frac{r}{D/2}$$

$$\alpha = \frac{2r}{D} = \frac{R}{WD}$$



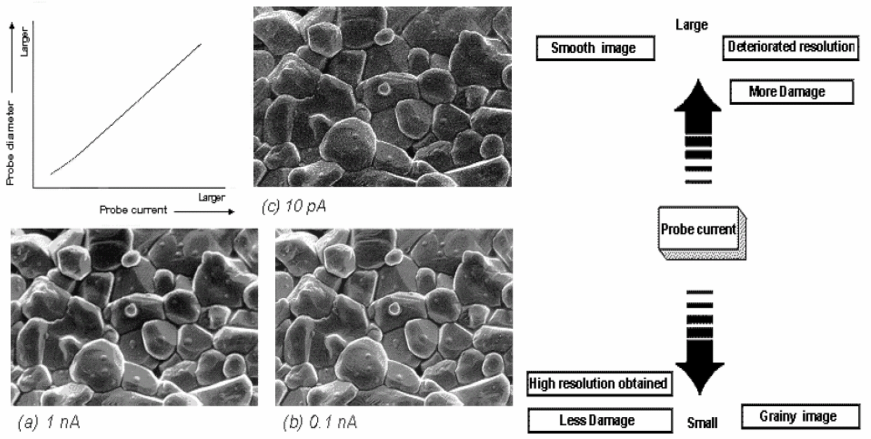


WD固定, R↑, D↓

Influence of image quality

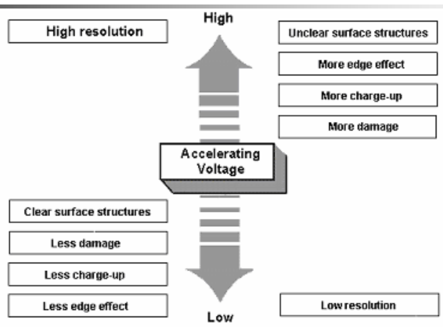
Influence of probe current and probe diameter

- 電子束電流對試片之影響



Influence of image quality

Influence of Accelerating voltage

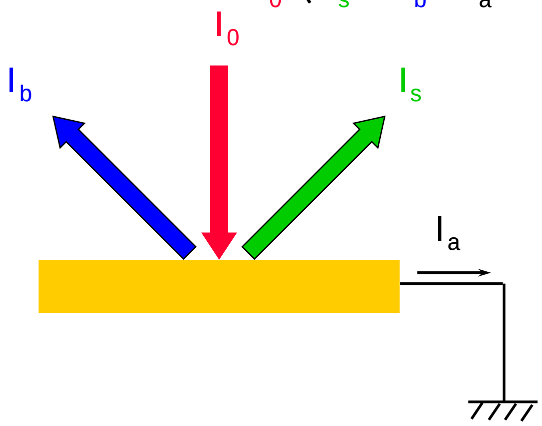


There are some unnegligible demerits in increasing the accelerating voltage.

1. detailed structures of specimen surfaces.
2. edge effect.
3. charge-up.
4. specimen damage.

Influence of charge-up

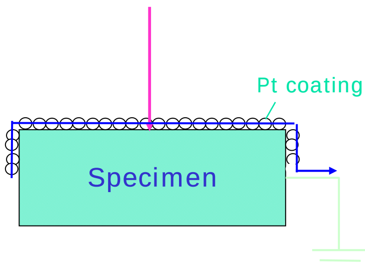
$I_0 \neq I_s + I_b + I_a$ ⇒ **Charge-up**



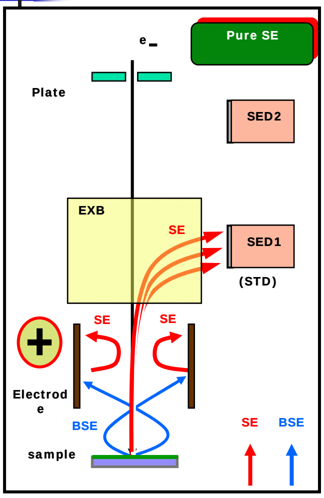
- I_0: Primary Beam
- I_s: Secondary Electron
- I_b: Back scattered Electron
- I_a: Specimen Current

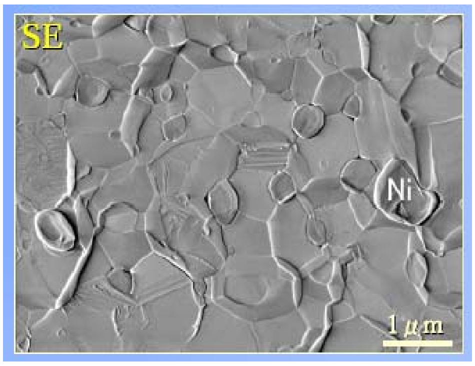
Influence of image quality
Reduction of charge-up

Specimen coating



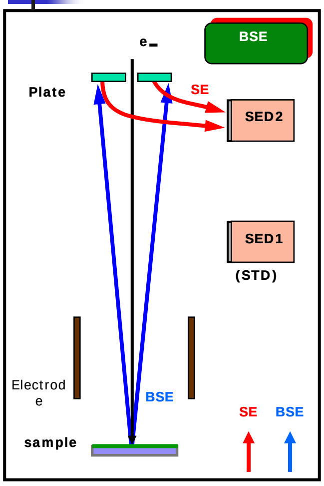
Signal detection **(SE)**

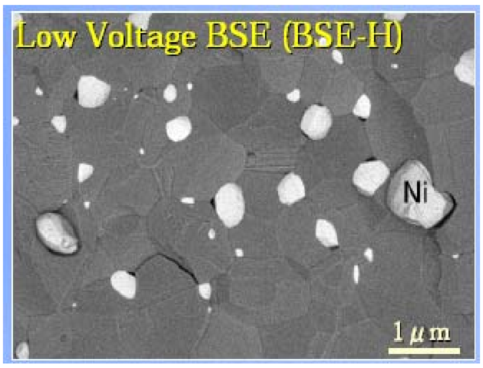




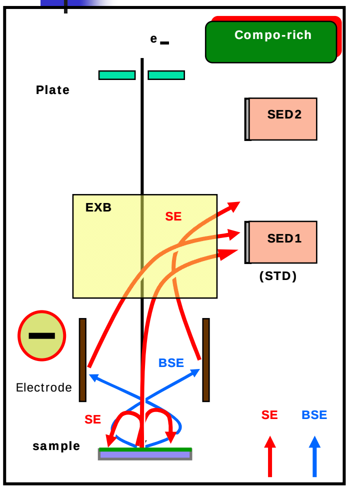
Topmost surface

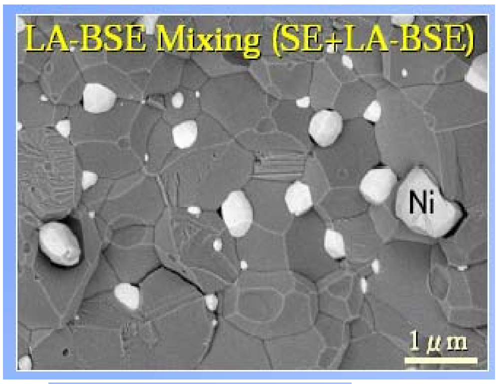
Signal detection (BSE)





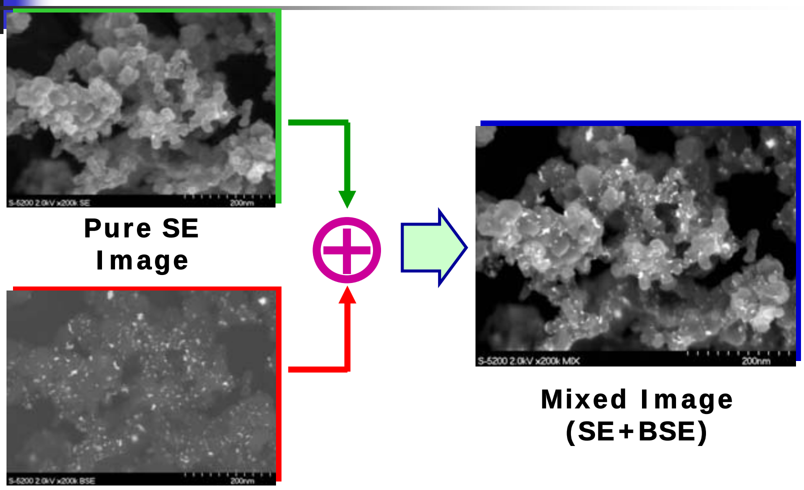
Signal detection **(SE +BSE)**



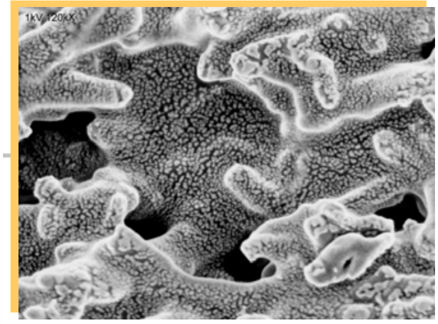


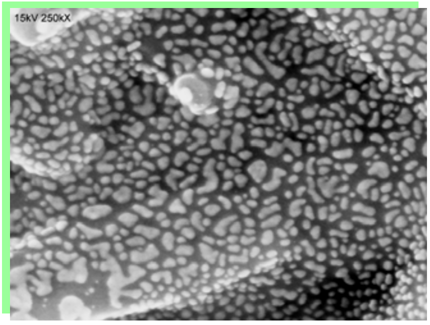
Surface + Composite

High resolution image



SU-70





Focus Ion Beam (FIB)

What a FIB does that a SEM does not

- Removes Material
- Adds Material
- Secondary Ion imaging shows material contrasts
- Channeling Contrasts
- Prepares samples in situ
- Combines high magnification imaging and sample modification

FIB Column Compared to SEM column

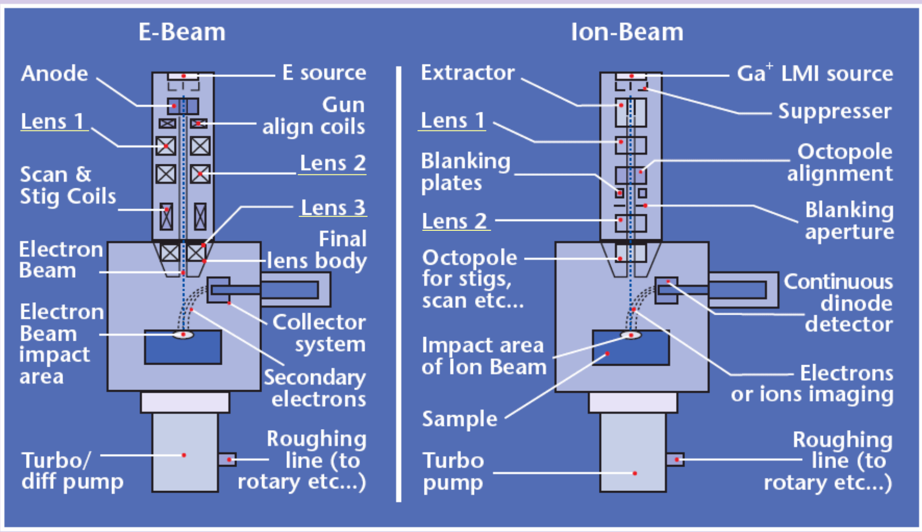
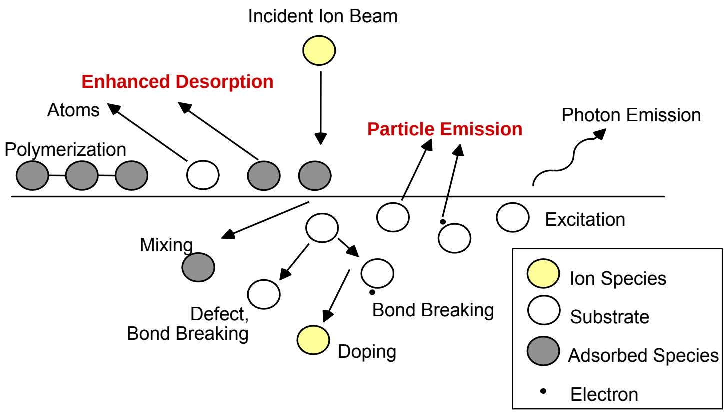


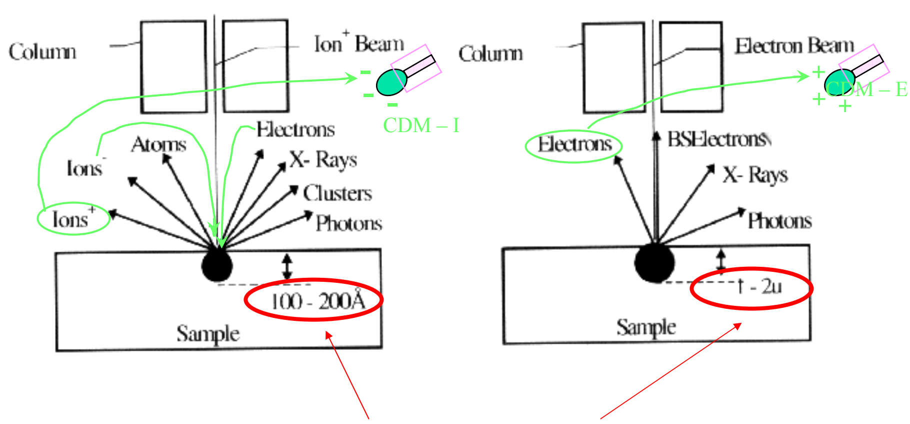
Figure 8: Schematic presentation of SEM and FIB and the many similarities of the instruments.

Ion Beam to Sample Interactions



Beam-Solid Interactions

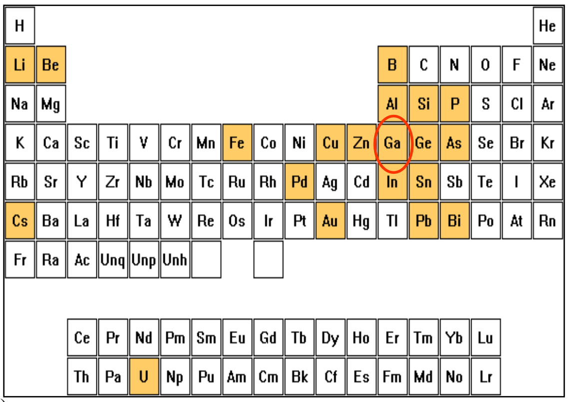
Ion Beam **Electron Beam**



Note difference in interaction volume

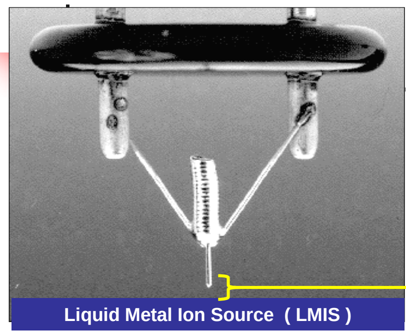
Ion Source

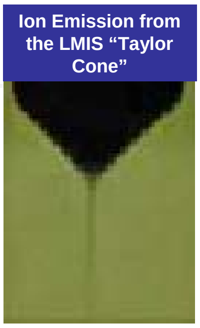
- A liquid metal
- Room temperature operation
- Long lived (500-1500 hr sources)
- High vacuum compatible
- Large ion for sputtering

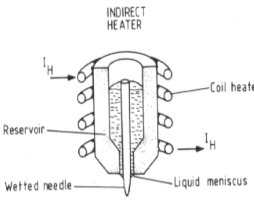


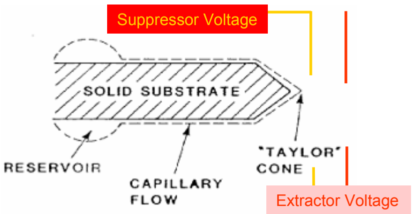
LMIS's have been made from many materials!

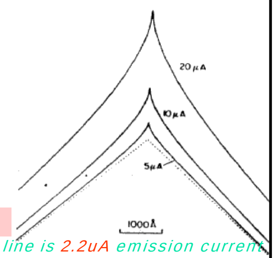
Liquid Metal ion Source (LMIS)







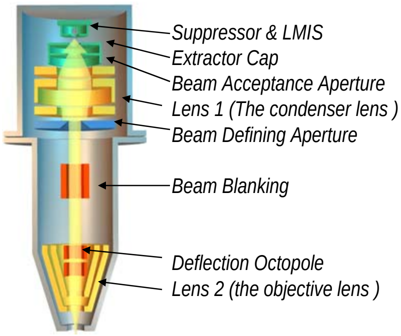




Dotted line is 2.2uA emission current

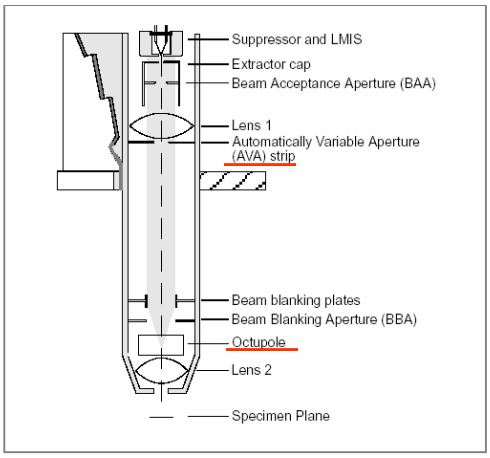
The Ion Column

Magnum Column

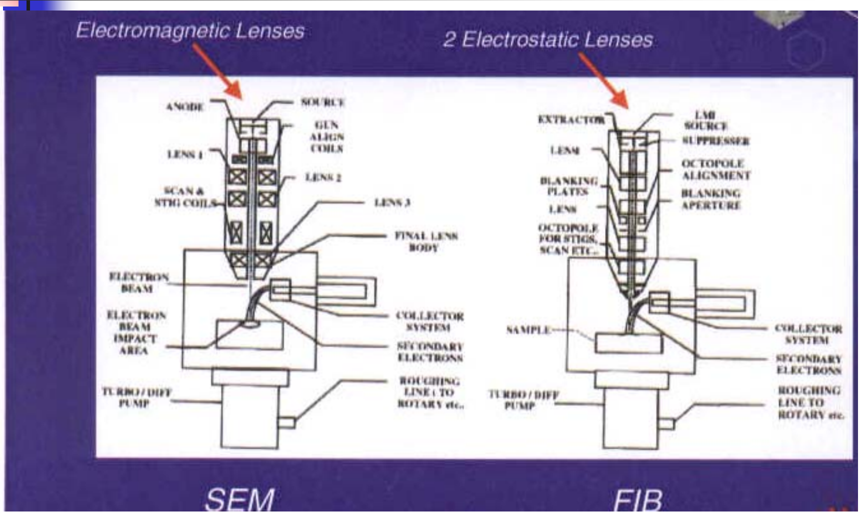


Cylindrical octopole lenses may be used to perform multiple functions such as **beam deflection**, **alignment**, and **stigmation correction**. In addition, **the scan field** can be **rotated** using octopole lenses.

Figure 13-2 Magnum Column Schematic Drawing



SEM Compared to FIB



Aperture Strip

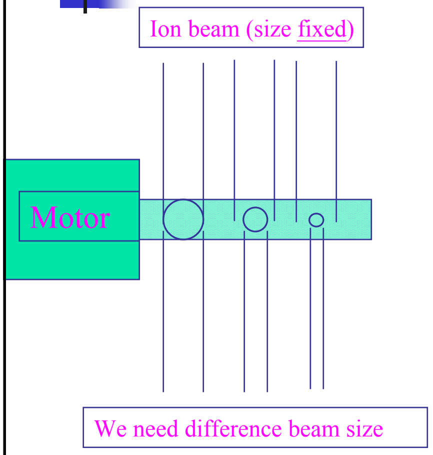
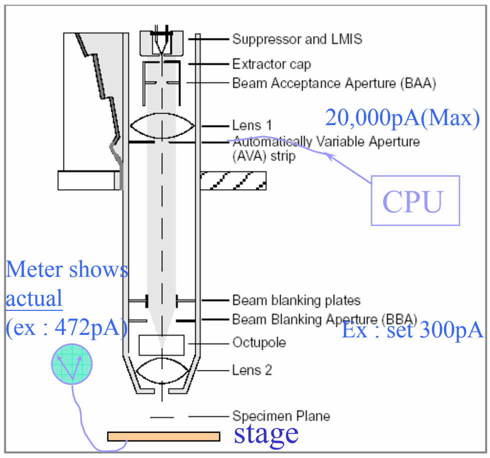


Figure 13-2 Magnum Column Schematic Drawing



FIB Aperture Settings

Aperture	Use
1 pA	High resolution imaging
10 pA	High resolution imaging
30 pA	High resolution imaging, small cross-section cleaning
100 pA	General imaging, cross-section cleaning
300 pA	Imaging, cross-section cleaning
500 pA	Cross-section cleaning
1000 pA	Medium bulk mill or large cross-section cleaning
3000 pA	Large cross-section bulk milling
5000 pA	Rough bulk milling
7000 pA	Rough bulk milling for large cross-sections
20000 pA	Extremely rough bulk milling for large cross-sections

Detectors

CDM : Channel Dynode Electron Multiplier

A Secondary particle detector:

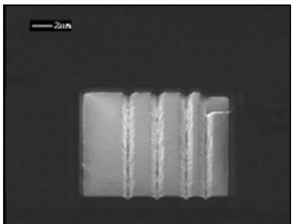
- **-I : in secondary ion mode**
- **-E: in secondary electron mode**

CDM: offers an view of the sample that is helpful in determining topographical information

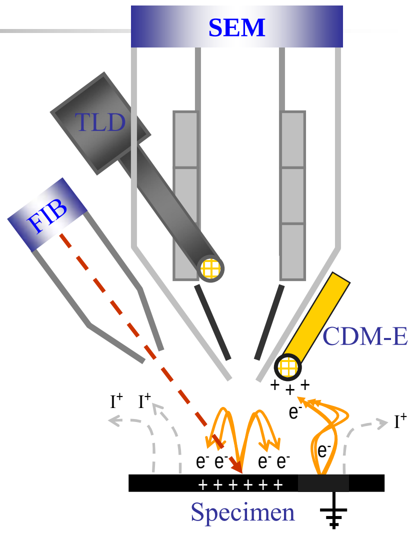
CDM-I: when the sample is charging, to obtain a better image at low magnifications

FIB imaging with the CDM-E

- **CDM - Secondary Electron Mode**
  - Detector biased **positive**
  - Images generated from **e⁻**
  - Emitted from top **50-100** Å
  - Charging images appears dark
  - Oxides dark, grounded metals bright
  - Voltage contrast observed



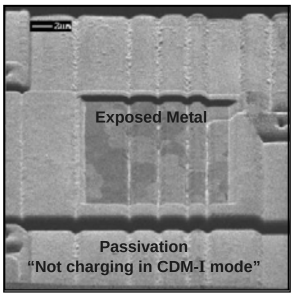
Passivation
“Charging in CDM-E mode”

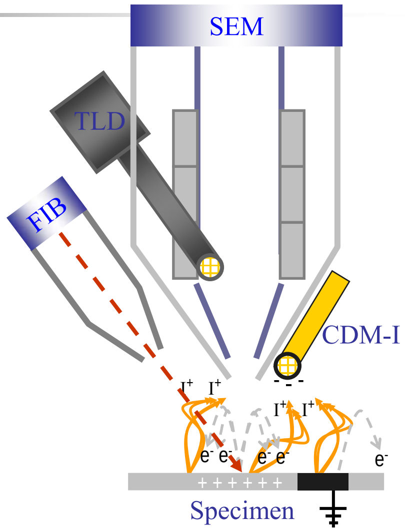


FIB imaging with the CDM-I

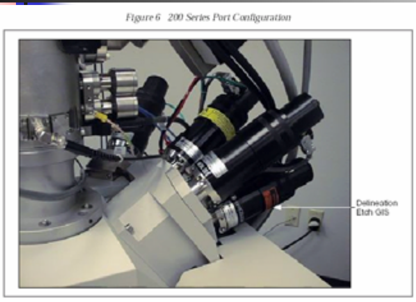
CDM - Secondary Ion Mode

- Detector biased **negative**
- Images generated with **I⁺**
- Emitted from top **5-10** Å
- Very surface sensitive
- No voltage-contrast
- Oxides bright



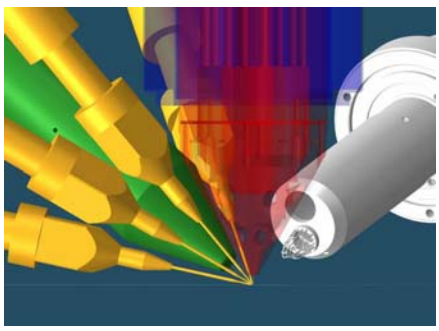


Gas Injection System (GIS)



Available gas source

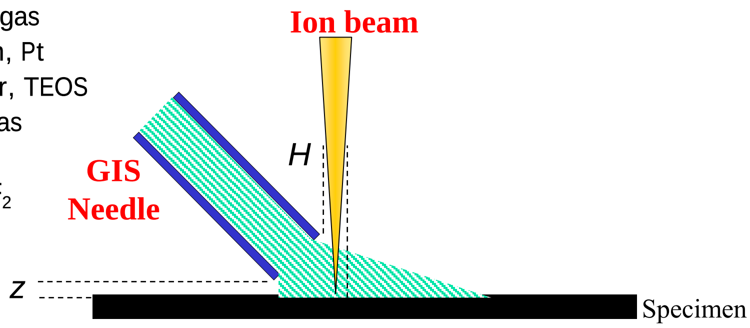
- •Platinum (Pt)
- •Insulator (IDE, TEOS)
- •Enhanced etch (EE, I_2)
- •Insulator enhanced etch (IEE, XeF_2)
- •Delineation etch (DE, an oxide-specific gas)



Multi-needle system

Gas Delivery

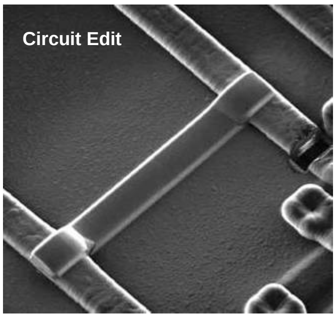
- Deposition and etching with reactive gas
- Deposited gas
  - * Platinum, Pt
  - * Insulator, TEOS
- Reactive gas
  - * EE, I_2
  - * IEE, XeF_2
  - * DE

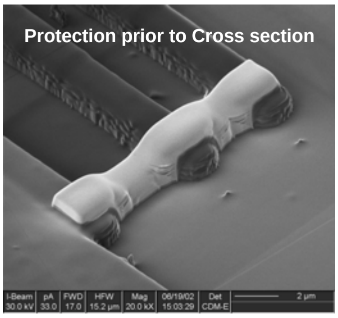


Z ≈ 50 ~ 75 μm, H ≈ 50 ~ 100 μm
Gas effective area 100 ~ 200 μm.

Platinum Deposition

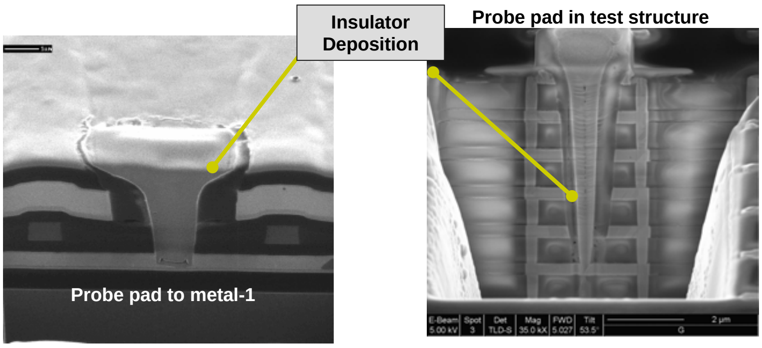
- **Chemical: Methylcyclopentadienyl(trimethyl)platinum(IV)**
- **Very hard: tougher for probing and thermal cycling.**
- **Chemically resistant**
- **Fast deposition rate**
- **User refillable**
- **Operating Temperature 38°- 42°C**





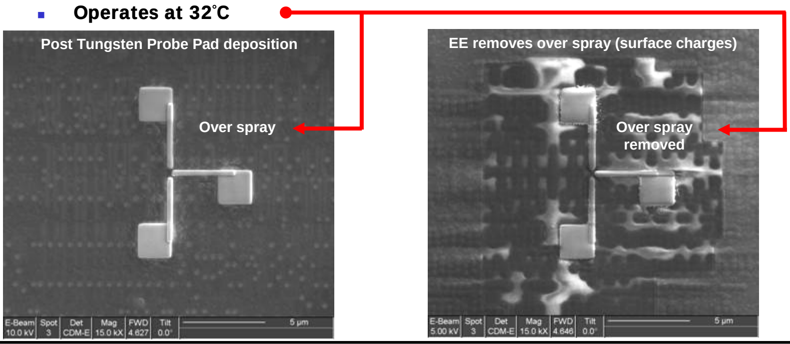
Insulator Deposition “Idep”

- Chemical: Tetraethyl orthosilicate
- Mixed with H_2O in needle to improve reaction
- In via structure, 1 Gohms resistance, 20 V breakdown
- Deposition rate for coatings is about 1µm / 20 minutes
- Operates at room temperature



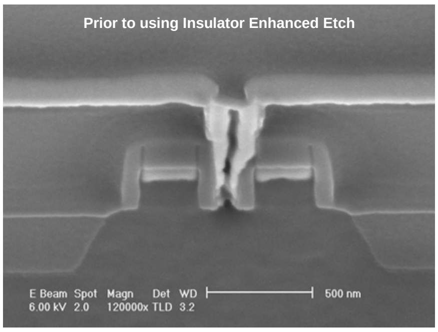
Enhanced Etch “EE”

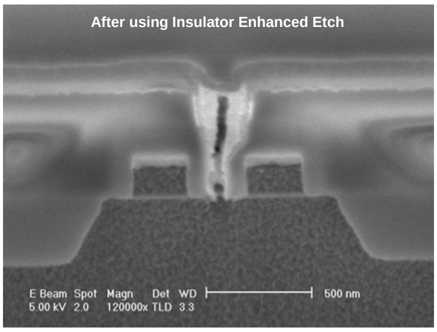
- Chemical: Iodine
- User refillable
- Metal selective etch about 10:1 (over oxide)
- Enhances Al sputter rate by15x
- Enhances Oxide sputter rate by 1x-3x
- Enhances Si sputter rate by 7x
- Removes metal deposition overspray
- Operates at 32°C



Insulator Enhanced Etch "IEE"

- Chemical: Xenon difluoride
- Oxide selective etch ~5:1
- Mills thermal oxide, TEOS ~8x than sputtering
- NOT user refillable
- Spontaneously etches silicon, polysilicon
- Yields highly resistive cuts
- Operates at room temperature

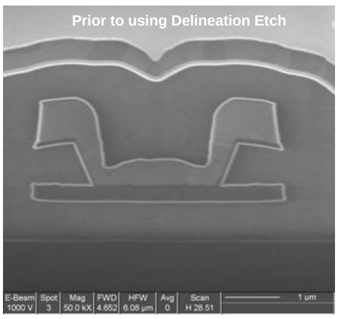




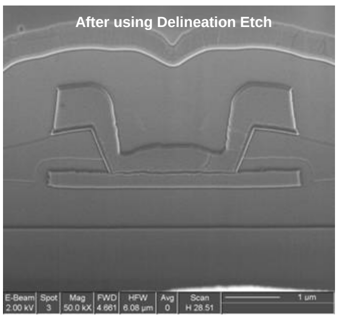
Delineation Etch "DE"

An oxide-specific gas

- Chemical: Trifluoroacetamide
- Create topographical contrast, exposing layer definition
- Selectively etches Oxides and Nitrides
- Does not damage Si

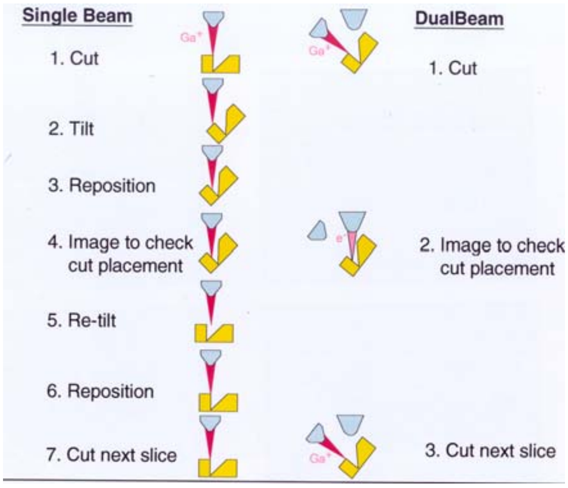


Before



After

Single beam and Dual beam difference



THE Dual-Beam SYSTEM

- A Dual-beam system consists mostly of:

  -Ion Source

  -Column

  -SEM

  -Detectors

  -Vacuum System

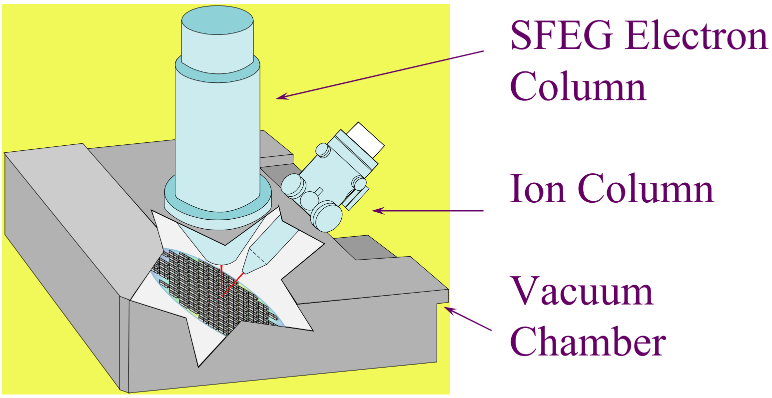
  - Gas Delivery

  -Stage

  -Computer with Integrated Image Processing

The Dual Beam System

Combining SEM and FIB systems!

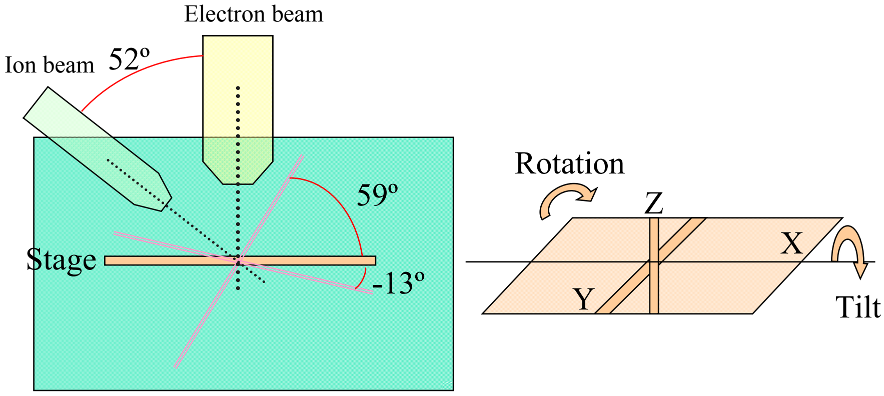


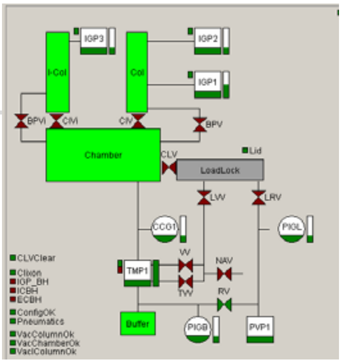
Chamber depicted here is an 8” dualbeam

The Dual Beam System

1.Electron beam used for taking picture.

2.Ion beam used for milling hole.





Pressures and TMP RPM

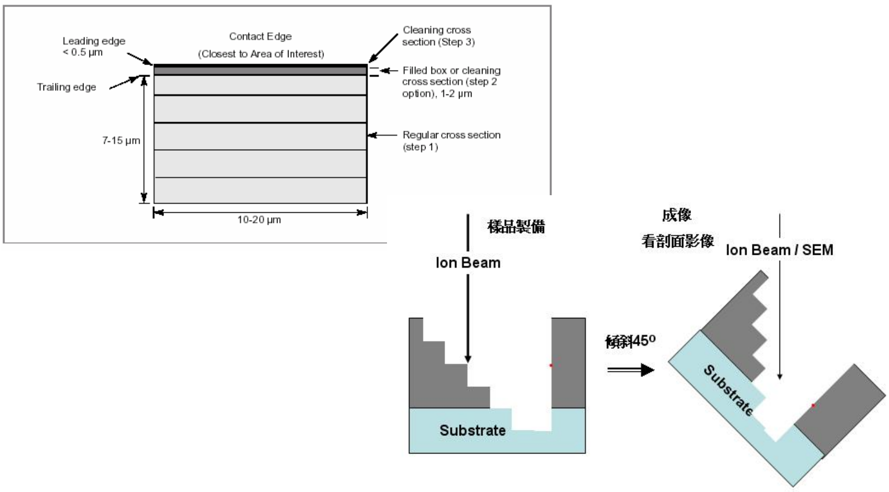
CCG1	7.05e-008 mbar
IGP1	3.24e-007 mbar
IGP2	1.52e-009 mbar
IGP3	3.03e-007 mbar
PIGB	1.87e-002 mbar
PIGL	2.49e-002 mbar
TMP1	101 %

APPLICATION

- X-section (Slice and view)
- Voltage Contrast (VC)
- TEM Sample preparation
- Circuit Edit
- Micromachining

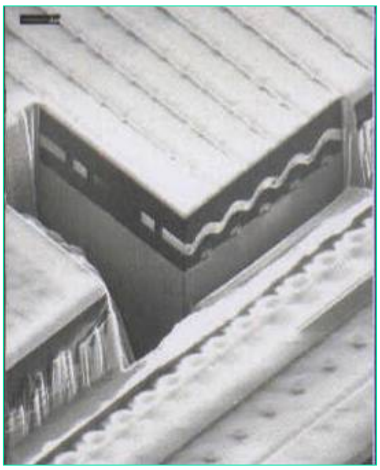
X-section (Slice and view)

Figure 4-18 A Typical Cross Section

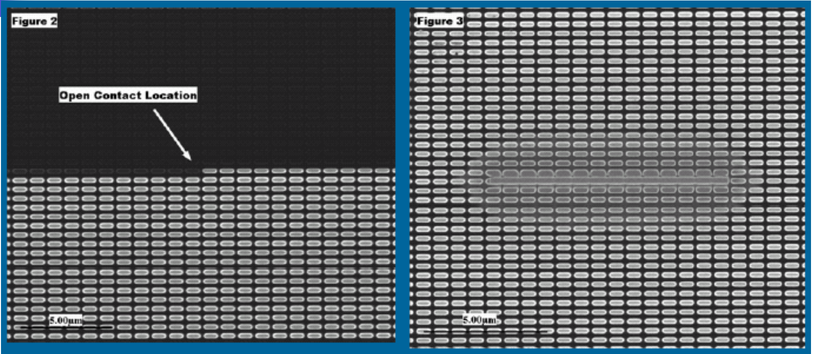


Corner cross-section

- Good for showing row and column structures
- Can see horizontal and vertical structure in one image



Voltage Contrast (VC)

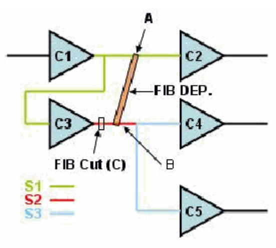


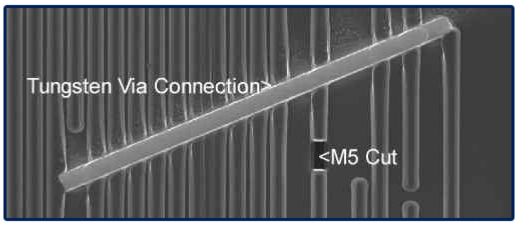
Open contact in chain shown by charging

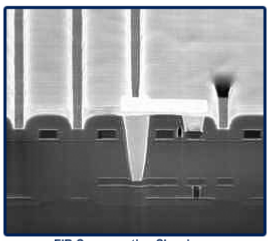
Bridging open contact with metal deposition indicates remaining contacts are good

B. B. Rossie, et al., Microscopy and Microanalysis Proceedings (2000) 520

Circuit Edit



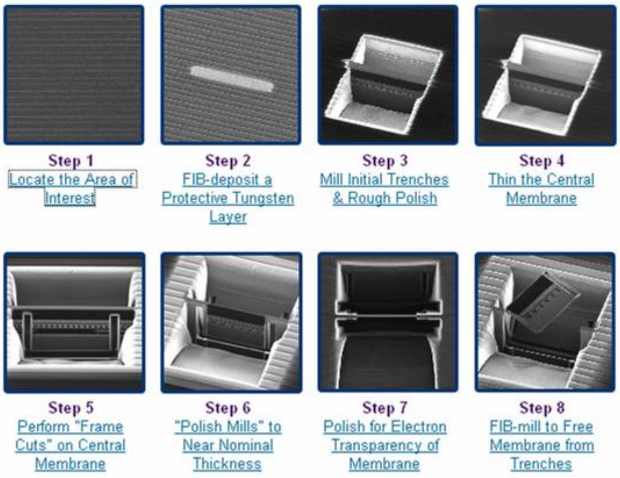




FIB Cross-section Showing Device Modification

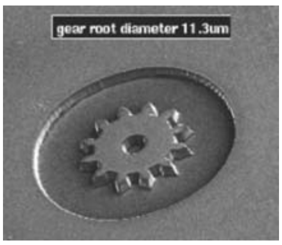
http://www.fibics.com/index.html

TEM Sample preparation



http://www.fibics.com/index.html

Micromachining



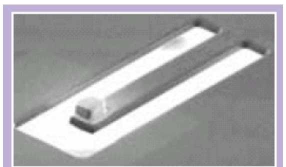
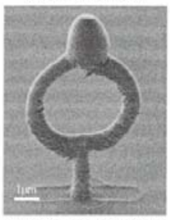


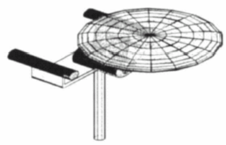
Figure 21: Cantilever with proof-mass machined from a Si_3N_4 membrane.

(a) 3-D CAD model

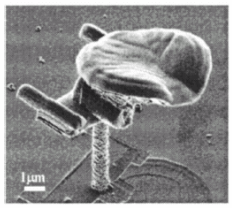


(b) SIM image (tilt 45deg)

Fig. 8. Micro ring with 4.3 μm external diameter.



(a) 3-D CAD model



(b) SIM image (tilt 45deg)

Fig. 7. Star Trek, spaceship Enterprise NCC-1701D's micro model, 8.8 μm long.

thank you!