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ADVANCED FE APPLICATIONS COURSE

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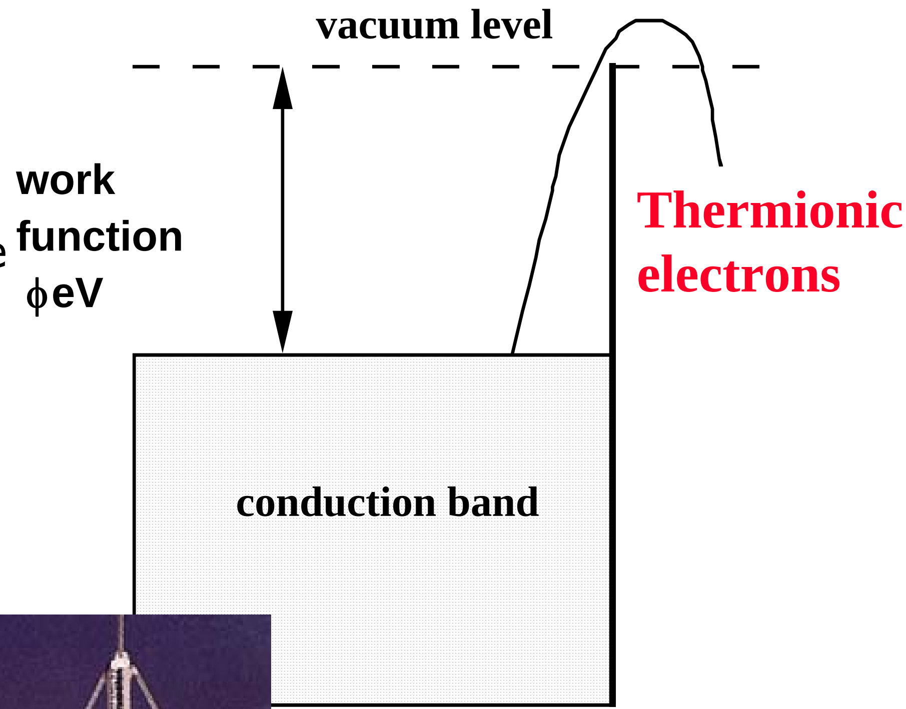
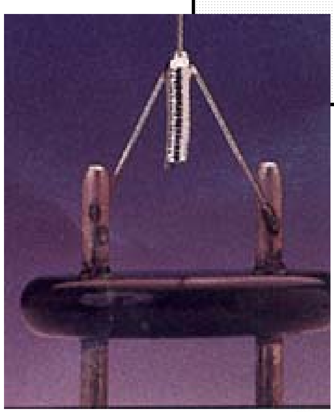
Theory of Microscopy

Thermionic Emitters

- Boil electrons over the top of the energy barrier
- The current density depends on the temperature and the cathode work function
- Cheap to use, modest vacuum required (W only)
- Can also use LaB_6 which has a better performance but requires a higher quality vacuum

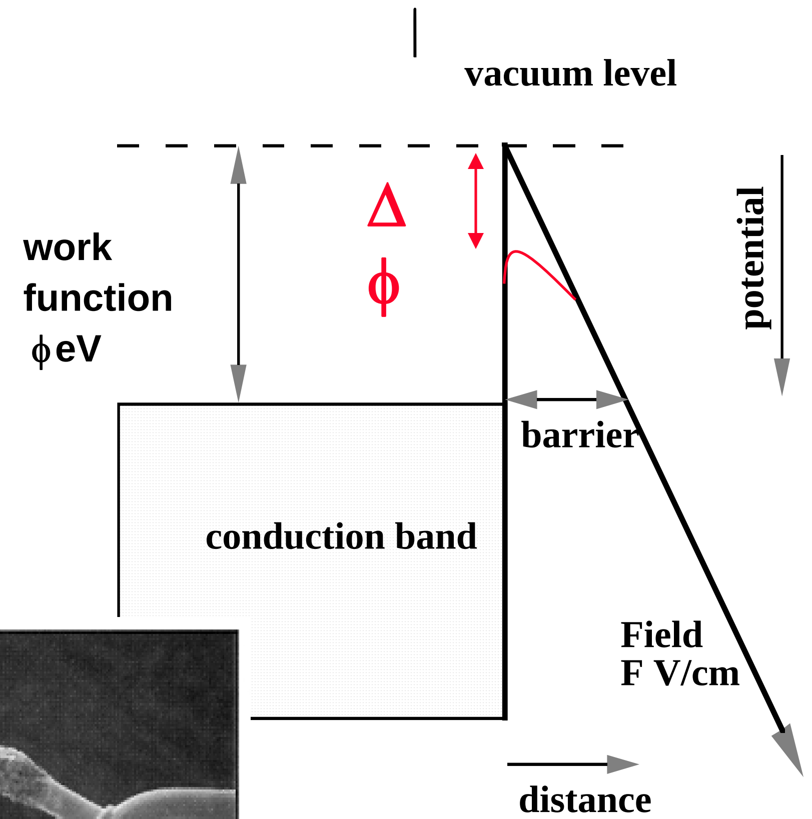


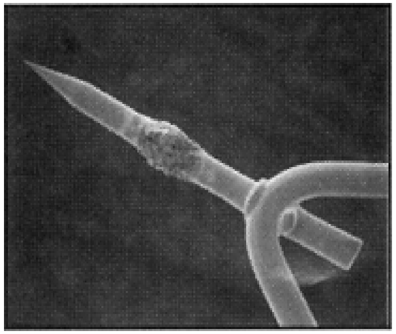


Schematic Model of Thermionic Emission

Schottky FEG

- In the Schottky emitter the field F reduces the work function ϕ
- Cathode behaves like a thermionic emitter
- The cathode is modified by adding ZrO to lower the value of the work function ϕ
- A Schottky gun is a field-assisted thermionic emitter
- **Resolution suffers at low voltages due to larger energy spread**
- **Life is much shorter than the cold field emitter. 2years or less (ie:SU70 vs. SU8000**
- **Power interruptions with Shottky causes tip re-conditioning which can take up to one day**

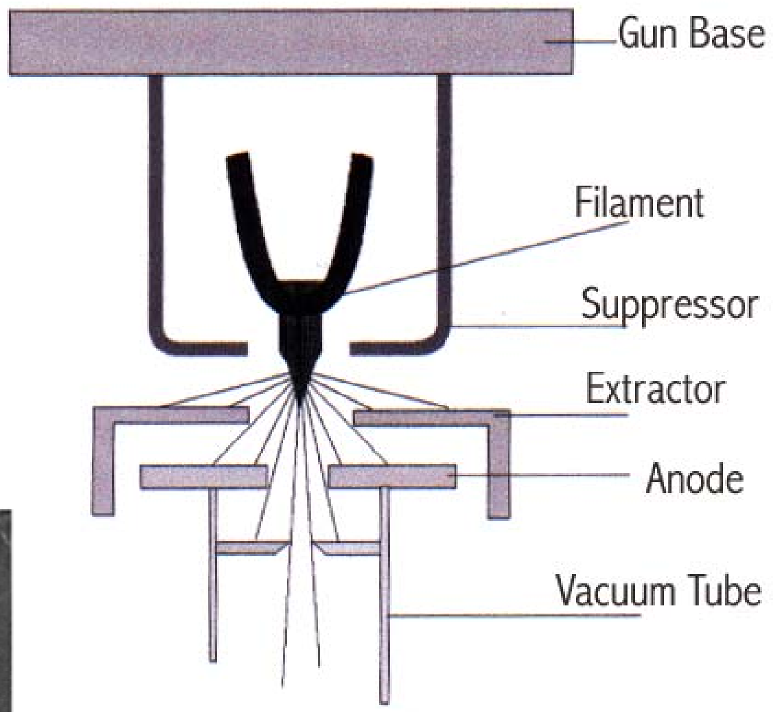


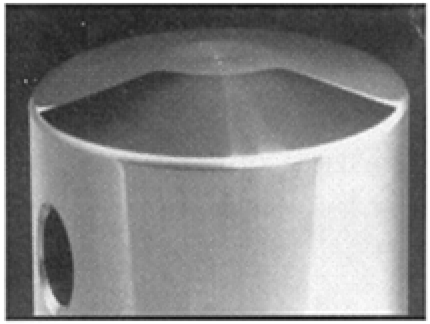

ZrO dispenser

The Schottky Emitter

» The tip is welded to a filament and is then centered mechanically in the Suppressor electrode which prevents stray thermionic emission from passing down the column

» The voltage on the extractor electrode controls the emission current from the gun

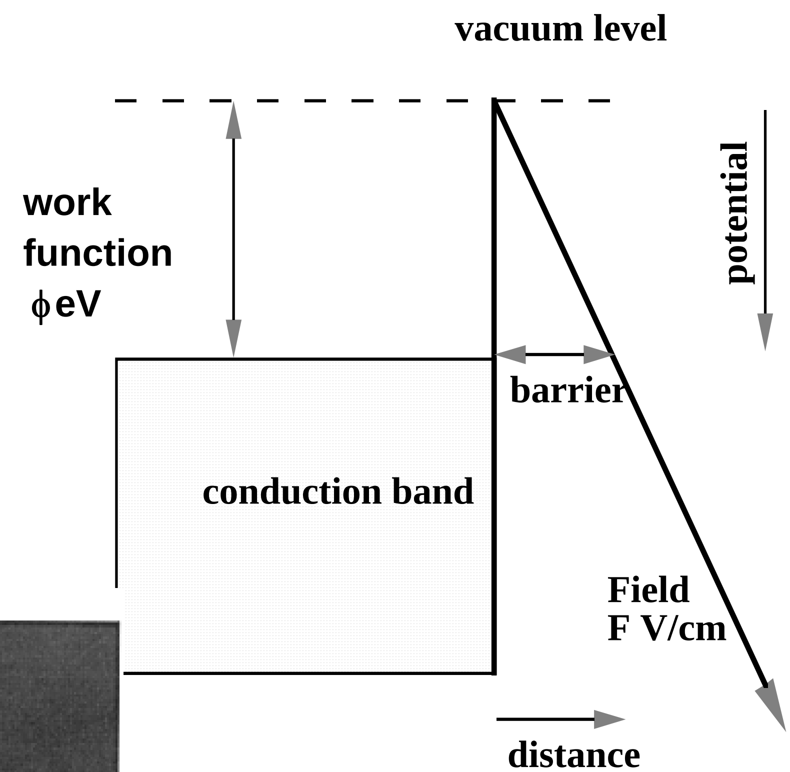


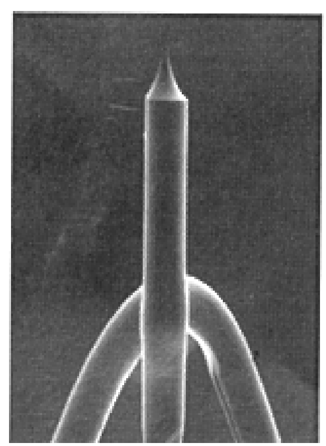


TFEG suppressor cap

Cold Field Emitters

- Electrons tunnel out from the metal because of the high field
- The field is obtained by using a sharp tip (1000Å) and a high voltage
- The emission is temperature independent.
- Needs UHV but gives long life and high performance. Typical lifetime is 7 years or longer
- Has higher resolution than Shottky at low voltage because of lower energy spread.
- Impervious to power interruptions. No downtime even after days of no power.





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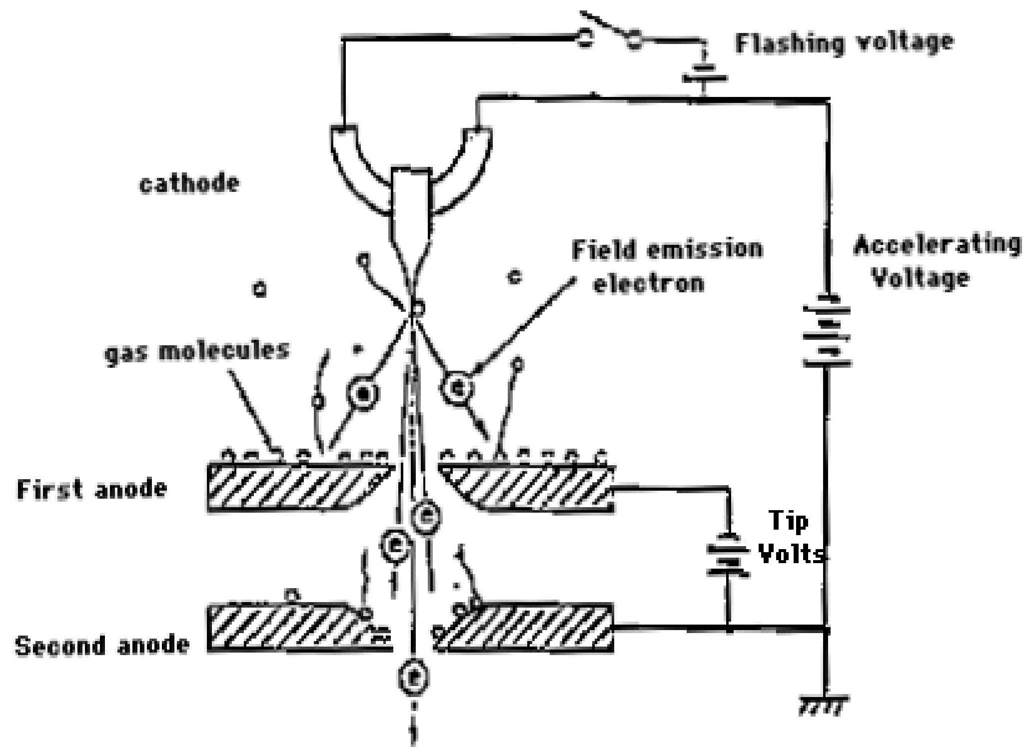
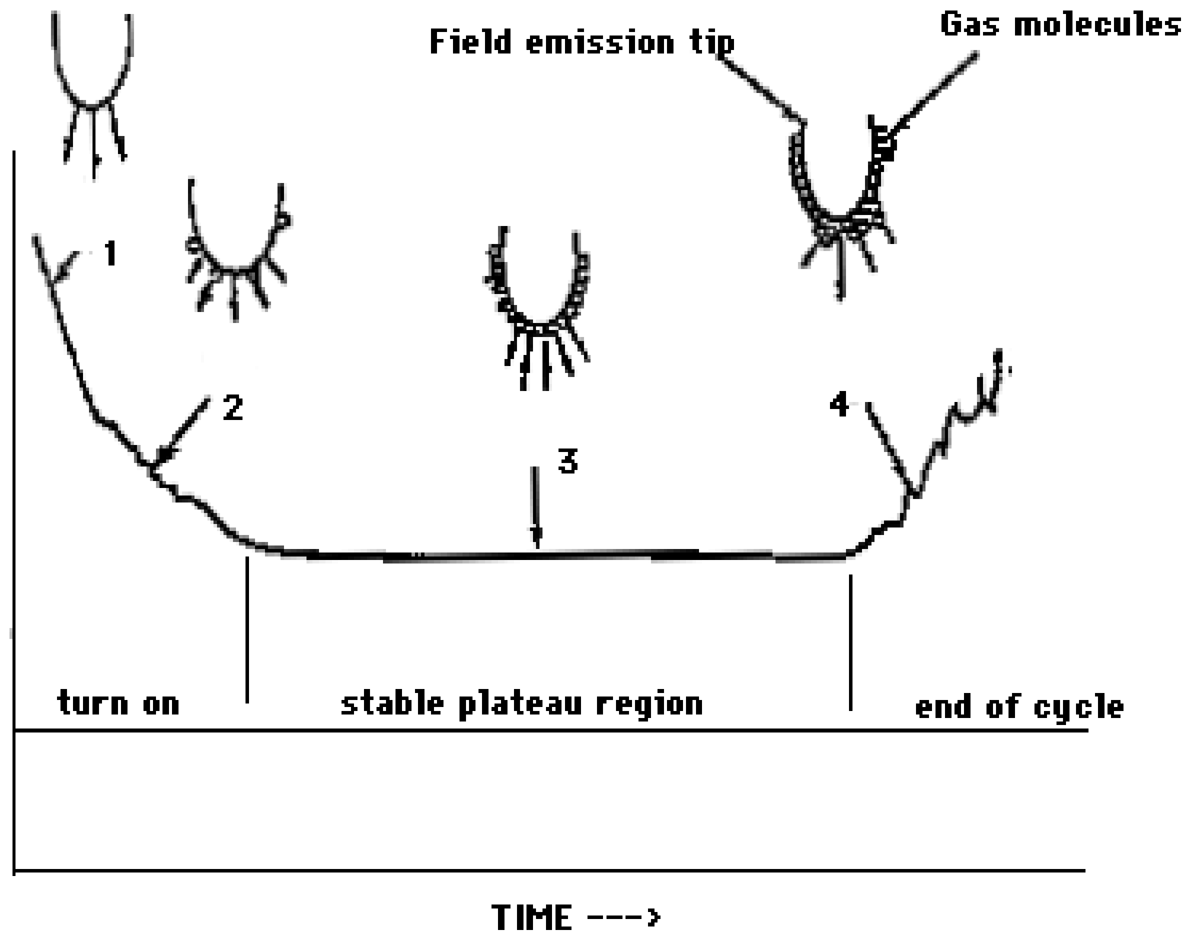
Gas production

- The tip gets dirty...
- Gas molecules are desorbed from 1st anode by electrons
- Some of these stick on the tip making it less sharp
- This causes the emission current to fall over time



The life cycle of an FEG tip



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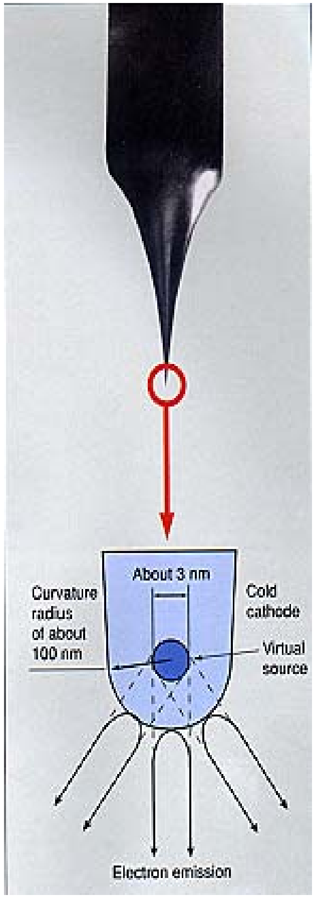
Comparing emitters

- The various types of electron emitters can be compared by looking at three parameters - brightness, source size, energy spread
- Other quantities are also important - e.g vacuum required, lifetime, cost, expected mode of use of SEM

Source Size

- …is the apparent size of the disc from which the electrons come
- Small is good - for high resolution SEM less demagnification
- Big is sometimes good - e.g. for large probe sizes and high beam currents



- **Tungsten hairpin - 50µm diameter**
- **LaB_6 - 5µm**
- **Thermal FEG - 250Å**
- **Cold FEG - 50Å**
- **Nano-FEG - 5Å**

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Emitter brightness

- Brightness is the most useful measure of gun performance
- Brightness varies linearly with energy so must compare different guns at the same beam energy
- High brightness is not the same as high current

- At 20keV typical values ($A/cm^2/str$)
  - W hairpin 10^5
  - LaB_6 10^6
  - FEGs 10^8
  - nano-FEG 10^{10}

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Energy Spread

- Electrons leave guns with an energy spread that depends on the cathode type
- Lens focus varies with the electron energy (chromatic aberration) so a large energy spread spoils high resolution and low voltage images

- **Typical values**
- **W hairpin 2.5eV**
- **LaB_6 1.0eV**
- **Schottky 0.75eV**
- **Cold FEG 0.35eV**

colder

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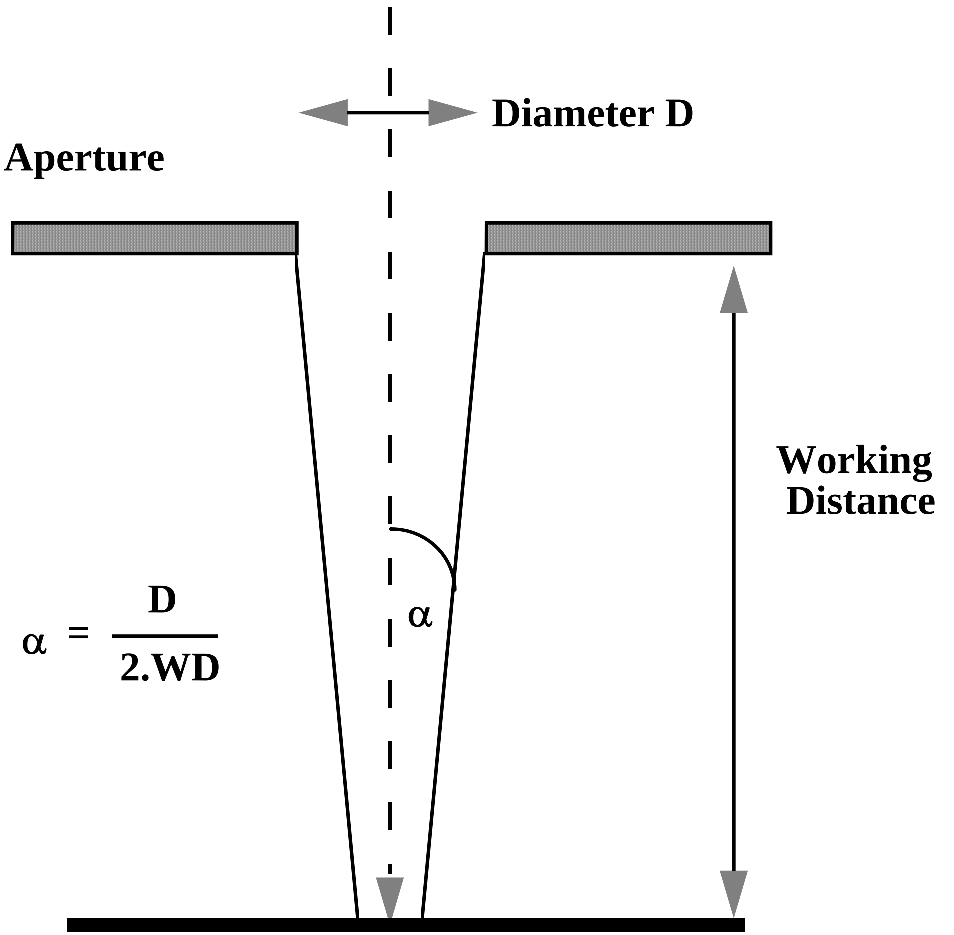
Apertures

- There are three types of apertures found in the FEGSEM
- Fixed (or spray) - prevent scattered electrons from traveling down column
- Moveable - define α the beam convergence angle
- Pickup - collect current for noise canceling or drift compensation

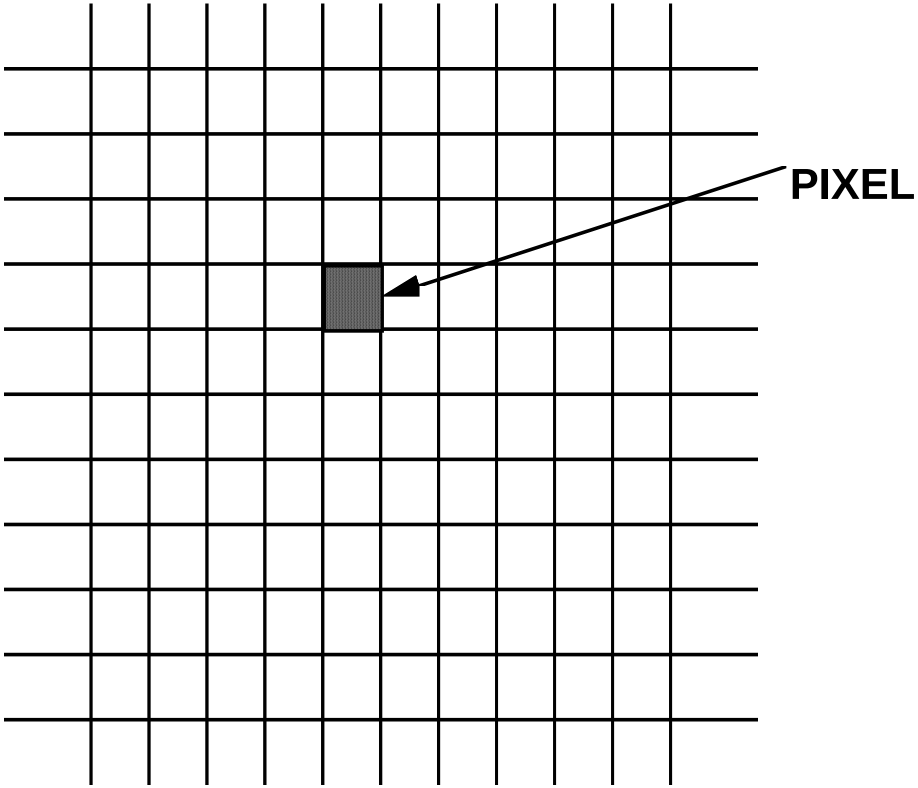
Apertures and α

- The final aperture defines α which is usually ~1- 20 mrad (i.e. smaller than 1/2 degree)
- When α is small the depth of field is high, the resolution is good, but the beam current is low
- When α is big - we get high current, but a big spot size and poor DoF



What determines image resolution ?

- The pixel is the smallest unit of image detail. Nothing smaller in size than a pixel is visible.
- The pixel size is set by the display screen (analog system) or by the computer set-up
- The pixel size is equal to the CRT pixel size divided by the actual magnification e.g a 100μm pixel at 100x gives 1μm resolution



Pixel limited Resolution

- For magnifications lower than about 10,000x or so the SEM resolution is limited by the pixel size.
- Only at the highest magnifications is the probe size of the SEM the limiting factor.
- Resolution in the adjacent image is limited by pixel size because we know the beam can resolve the islands on the mag tape.

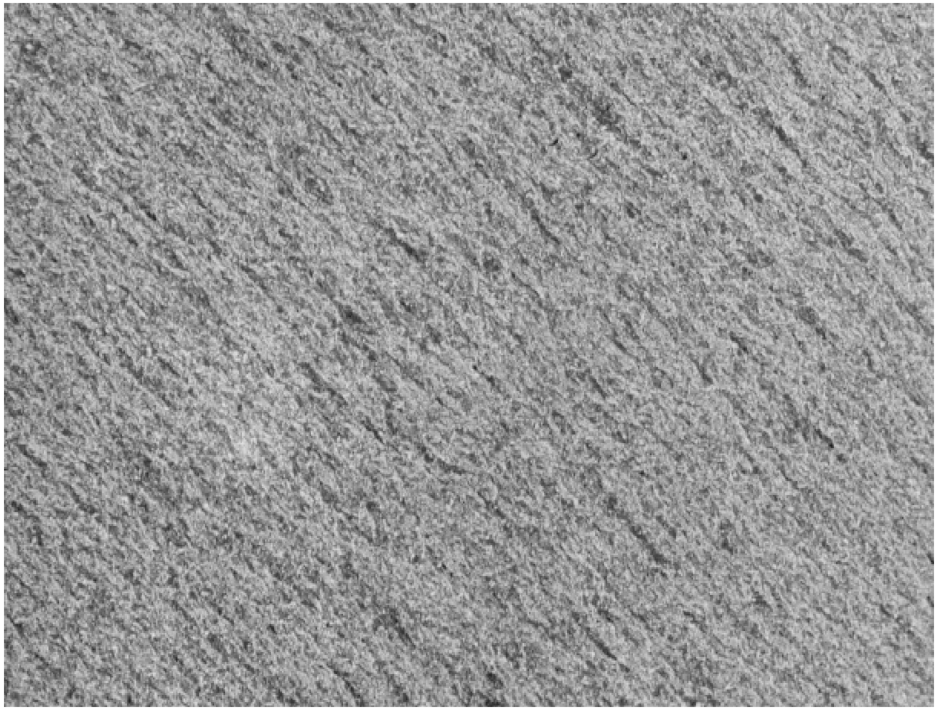
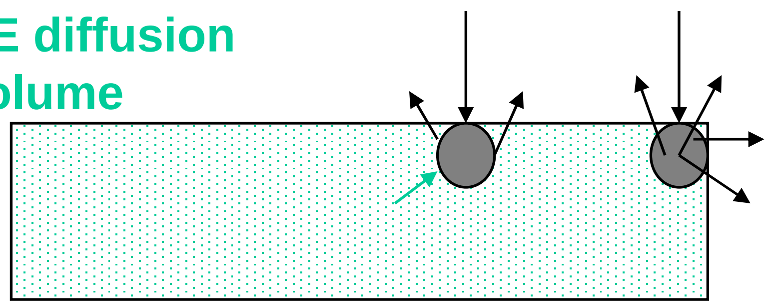


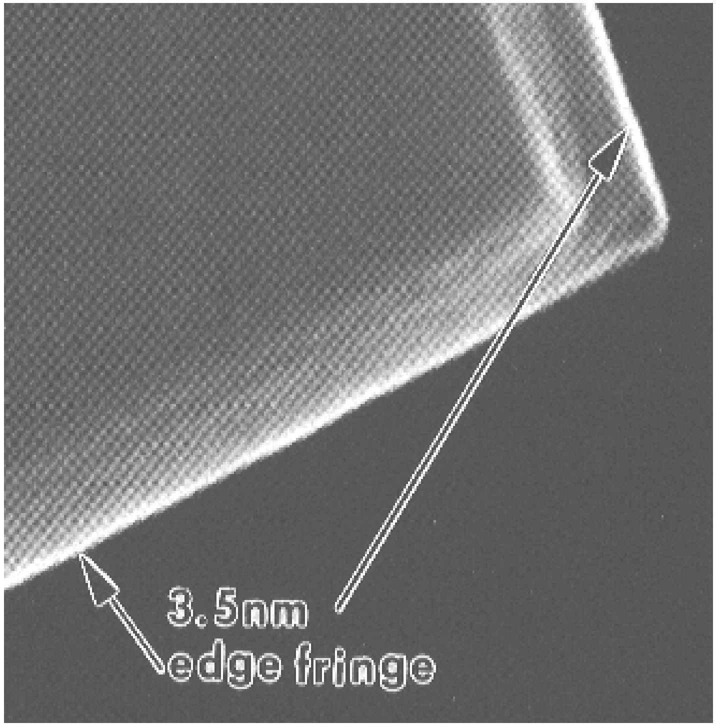
Image at 1kx magnification has 0.1µm pixel resolution

What limits SE resolution ?

- The 'bright white line' in high resolution images is due to extra SE emission
- The width of this line is a measure of the SE MFP
- The presence of this SE1 edge effect sets an initial limit to the achievable SE image resolution

SE diffusion volume

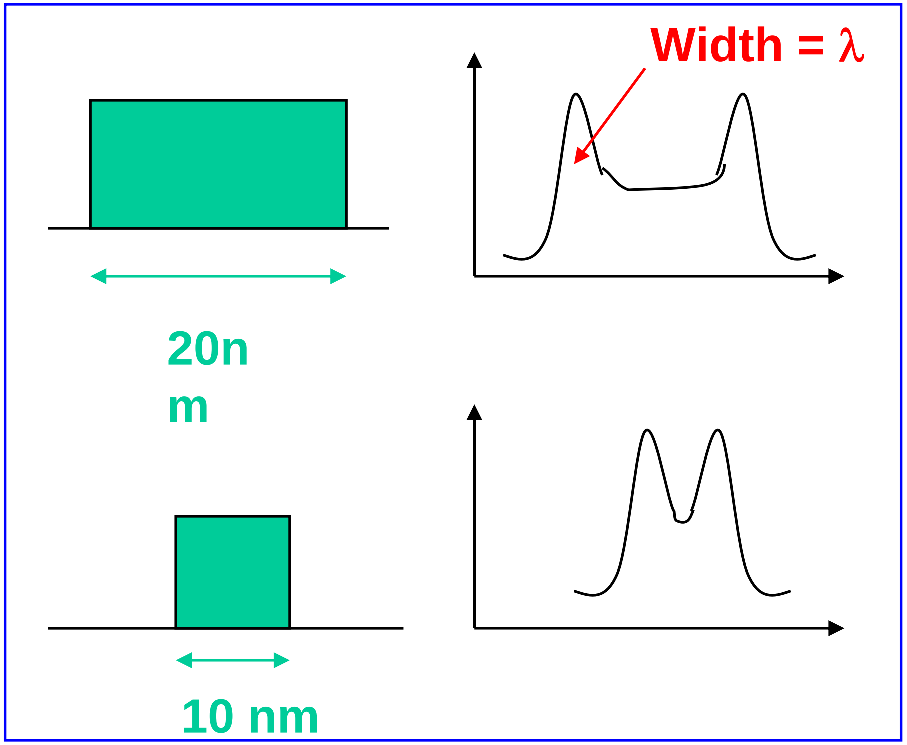




Molybdenum tri-oxide crystals
Hitachi S900 25keV

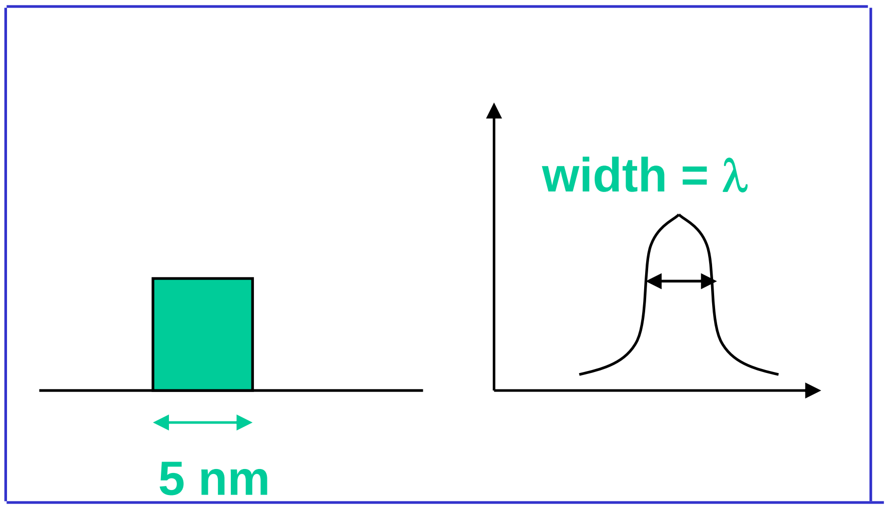
Classical resolution limit

- When the object is large its edges are clearly defined by the 'white lines'
- But as the feature reaches a size which is comparable with ☐ the edge fringes begin to overlap and the edge contrast falls



Classical resolution limit

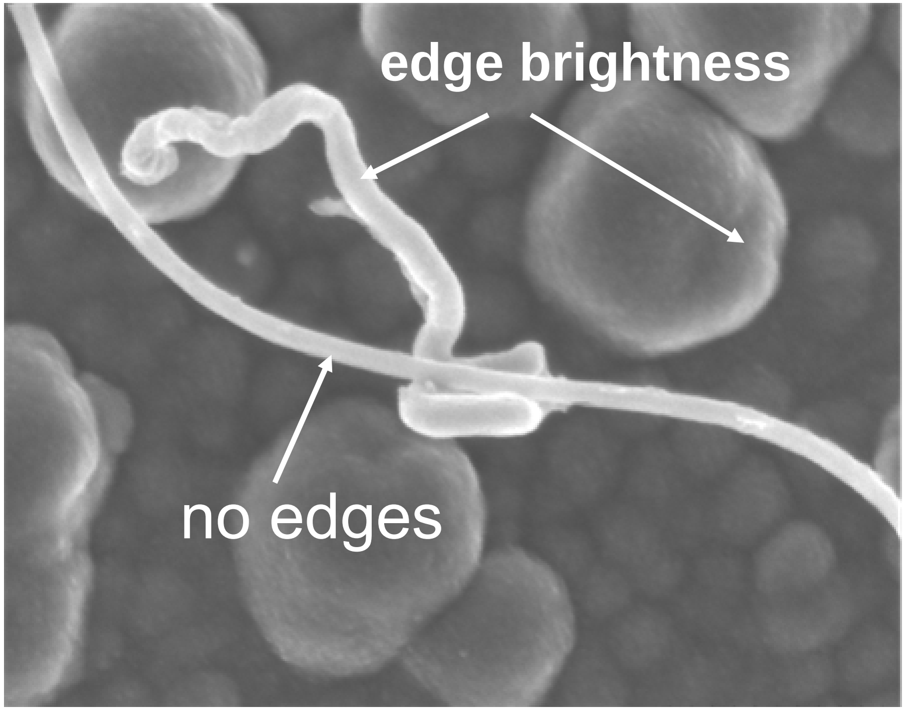
- When the feature size is equal to or less than l the edge lines overlap and the object is not resolved at all since it has no defined size or shape
- This is Gabor's resolution limit for SE imaging
- The resolution in SE mode therefore depends on the value of l



Particle contrast

In other samples...

- When an object gets small enough to be comparable with λ then it becomes bright all over and the defining edges disappear.
- For low Z, low density materials this can happen at a scale of 5-10nm



Carbon nanotubes

The resolution limit

- The resolution of the SEM in SE mode is thus seen to be limited by the diffusion range of secondary electrons, especially in low Z materials
- In addition the signal to noise ratio is always worse for the smallest detail in the image
- Improving SEM resolution therefore requires two steps:
  - minimizing or eliminating the spread of secondary electrons
  - improving the signal to noise ratio so that more detail can be seen
- The solution is to coat the sample