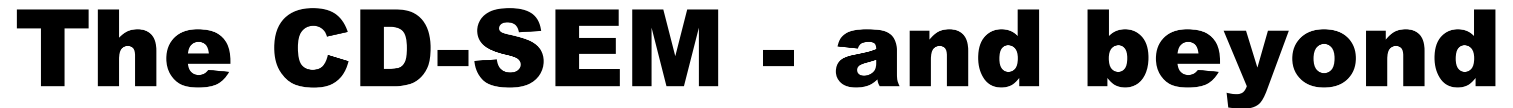
The CD-SEM - and beyond



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ULSI Austin TX March 27th

The CD-SEM

- For 30 years the performance of electron-optical tools has kept pace with the continuous reduction in feature size but it is no longer possible to anticipate continuous improvements by a factor of two times every three years *because the performance is now limited in some fundamental physical areas*
- The CD-SEM is subject to all the usual constraints that any SEM faces - but operational choices that have to be made can be mutually obstructive ......

Hitachi S-9300 CD SEM

Trends and Consequences

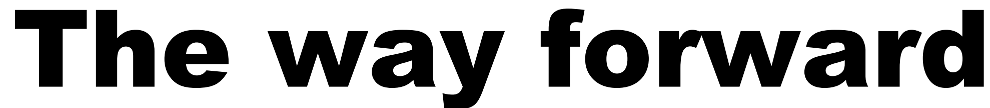
Parameter	Trend	Drivers	Consequences
Beam Energy	Lower	Charging Beam Damage	Degraded electron-optical performance Diffraction limited Low performance electron sources
Beam Current	Constant	Trade-off between throughput rate, damage and charging	Marginal signal to noise
Spot Size	Smaller	Resolution "Precision"	Lower beam current Degraded Signal/Noise Decreased depth of field
Scan Speed	Higher	Throughput Charge control	Stress on video components Poor linearity

- Each of the trends in the table represents a sensible response to a particular problem
- However these parameters interact in a complex way
- Lowering the beam energy to reduce charging and damage conflicts with the need for ever better imaging resolution
- Lowering the beam energy reduces the source brightness and reduces beam current - but smaller features and larger wafers demand high currents it throughput rates are to be maintained
- High scan speeds improve throughput and charging but lead to degraded linearity, and a lower signal to noise ratio

Issues and Solutions

Key Issue	Possible Solutions	Collateral Damage
Resolution	Aberration correction Higher beam energy	Higher beam current into a smaller probe, but collapse of the Depth of Field Higher beam current into a smaller probe. Depth of Field about constant
Charge Control	Still lower beam energies Low vacuum operation	Problem in maintaining optical performance Possible loss in resolution and contrast. Reduction in usable scan speed
Beam induced damage	Ultra-low energy High beam energies	Electron-optical performance Unproven
Contamination (carbon carry-over)	Low vacuum operation In situ cleaning	Possible loss in resolution and contrast. Reduction in usable scan speed Damage to resists and oxide layers. Time required
3-D information	“Stereo imaging” Modeling	Requires two exposures. Limited geometries Needs extensive pre-computation. Accuracy may be limited by charging
Throughput	Multiple columns Holographic methods	Complex technology and data handling. Statistical rather than site-specific data
Cost and delay in developing and delivering new tools	“Common Platform”	Needs agreement on basic specifications and creativity in design

The way forward

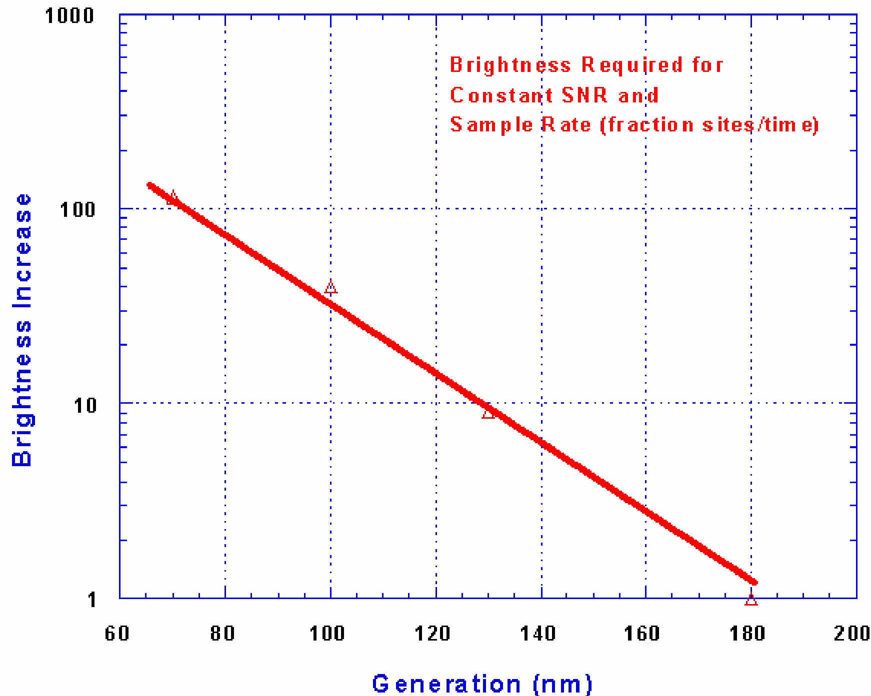


- There is no simple panacea because every choice carries with it an inescapable side-effect. A piecemeal solution is therefore impossible. Instead it is necessary to look at the tool as a complete system
- Can group options together to form scenarios for consideration:
  - the mixture as before (but hopefully better)
  - taking the high energy route
  - looking for something radically new

Option 1 - The mixture as before

- The obvious response is to keep the CD-SEM in the form in which it exists today and try to find some fixes to the problems identified above
- Since the CD-SEM is already operating at very close to its theoretical limits, and the restraints on progress are fundamental in nature, it is clear that this precludes the chance of any one advance resulting in a major step forward
- Instead progress must be made simultaneously in several different, key, areas of instrumentation

Key problems - The Electron Source



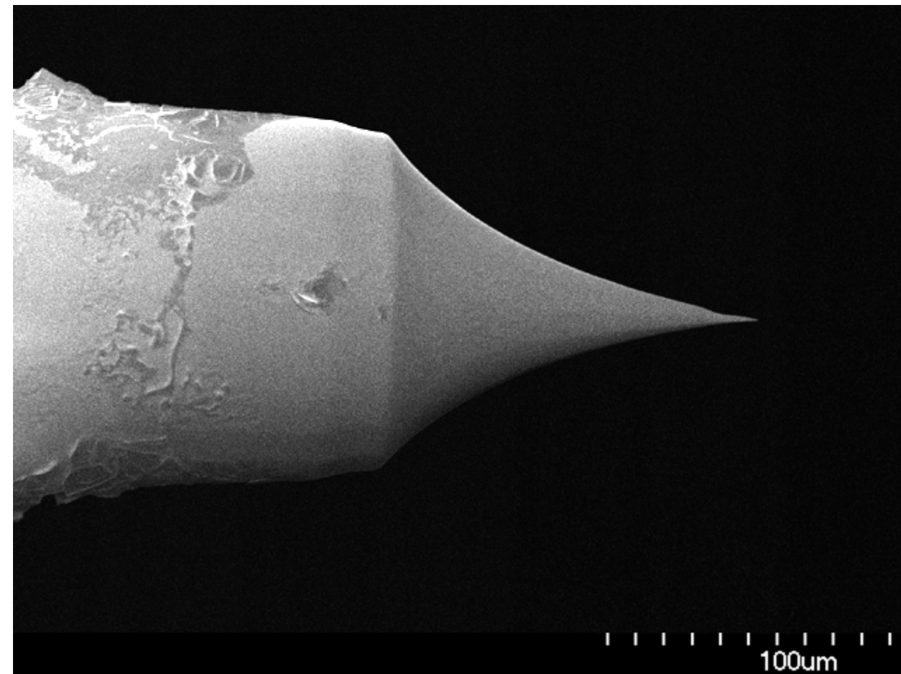
How brightness must be increased to maintain throughput and give enhanced resolution

- The brightness of an electron beam varies linearly with the energy with which it hits the target (Langmuir's Law)– thus a FEG source at 500eV is only about as bright as a tungsten hairpin filament at 20keV
- Most of the increased brightness obtained from the switch to FEG sources a decade ago is therefore used solely to maintain adequate performance at low energies
- To permit improved operation at lower energies - smaller spots, and higher currents - a much improved source is required. For the 70nm node a factor of 100x over current values is needed

This needs new technology -are Nanotips the answer?

- Nanotip field emitters can boost brightness by 50-100x compared to standard FEG
- Ideally suited to low energy operation (<500eV)
- Small source size ideal for making small spots
- NIST research (Vladar et al.) shows that nanotips could replace the usual FE tip in a CD-SEM to yield enhanced performance..
- But nanotips are cold, cannot be flashed, unknown lifetime

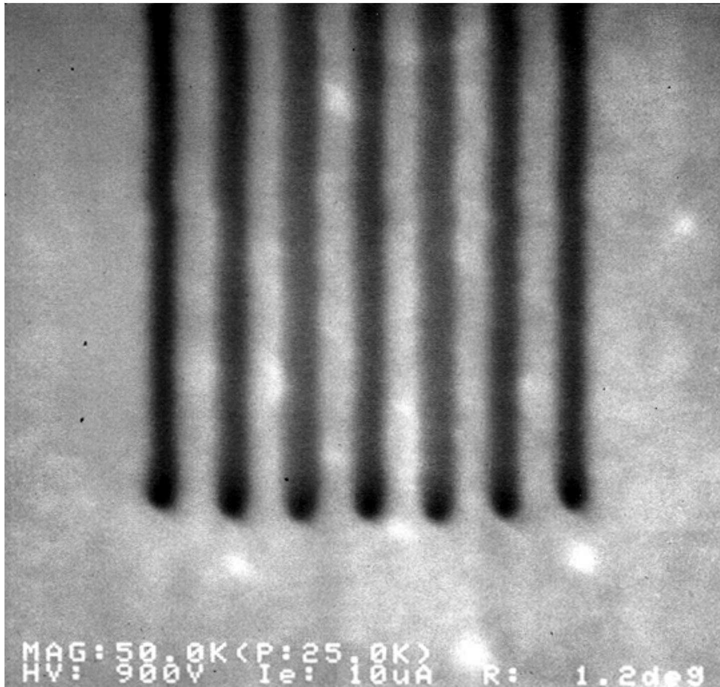
Courtesy Rick Silver, NIST

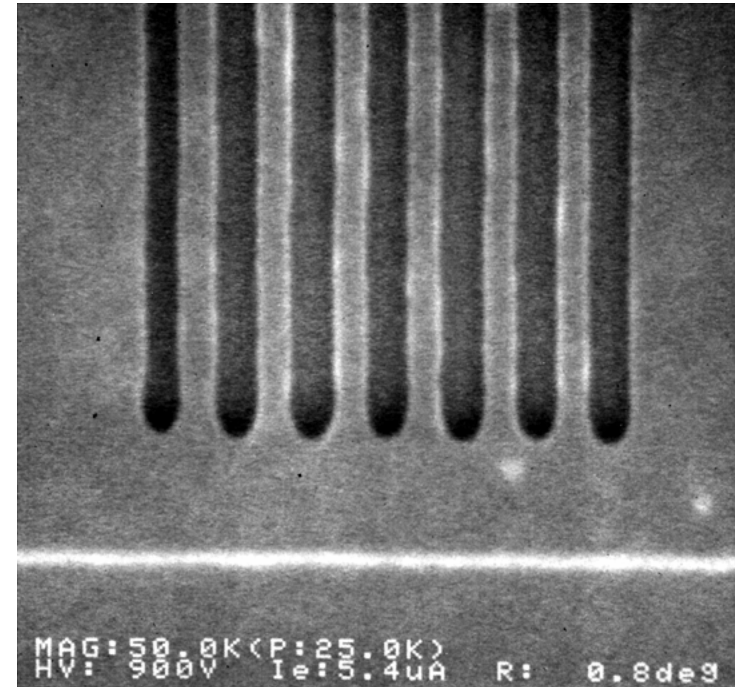


Nanotip field emitter

Comparing Regular and Nano Tips

AMAG PolySi sample





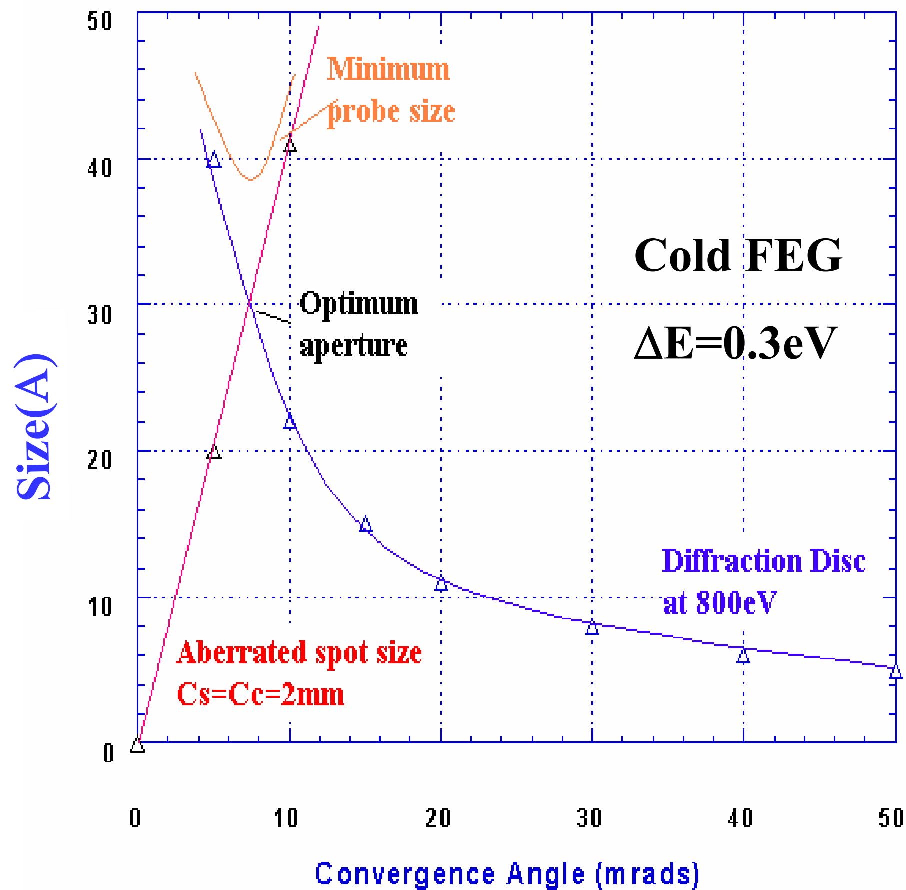
Regular FE tip

S-6000 CD SEM
1989

Nano tip

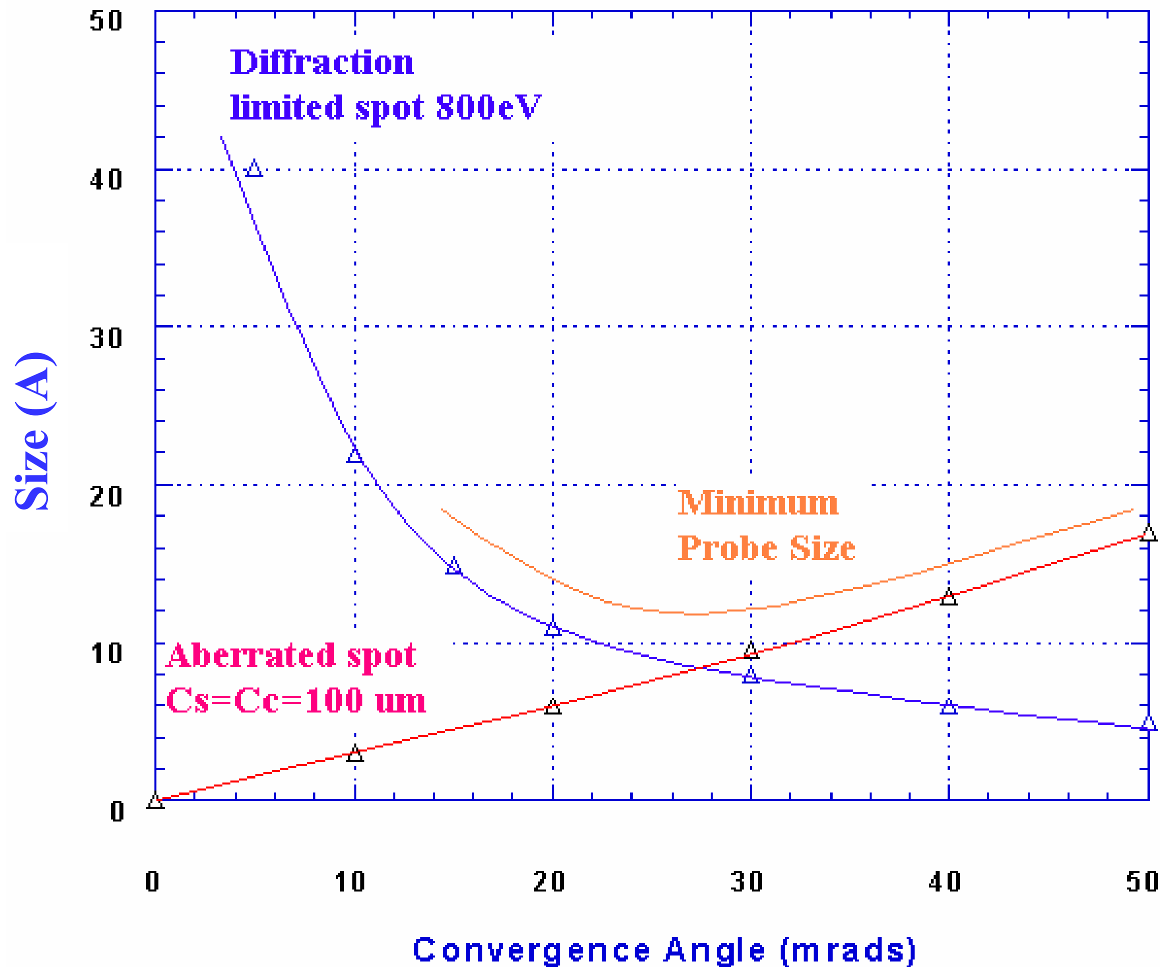
Courtesy A Vladar and M Postek NIST

Key Problems - Electron Optics performance



- Problem -the electron wavelength λ is large at low beam energies
- Problem - to minimize chromatic and spherical aberrations the numerical aperture (NA) of the lens has to be kept small
- Result - the diffraction disc (=λ/NA) limits the spot size
- For a CD-SEM lens this gives a probe size of a few nanometers at around 800eV (too big) and currents of a few pA (too small)
- However the small NA provides a reasonable Depth of Field in the image

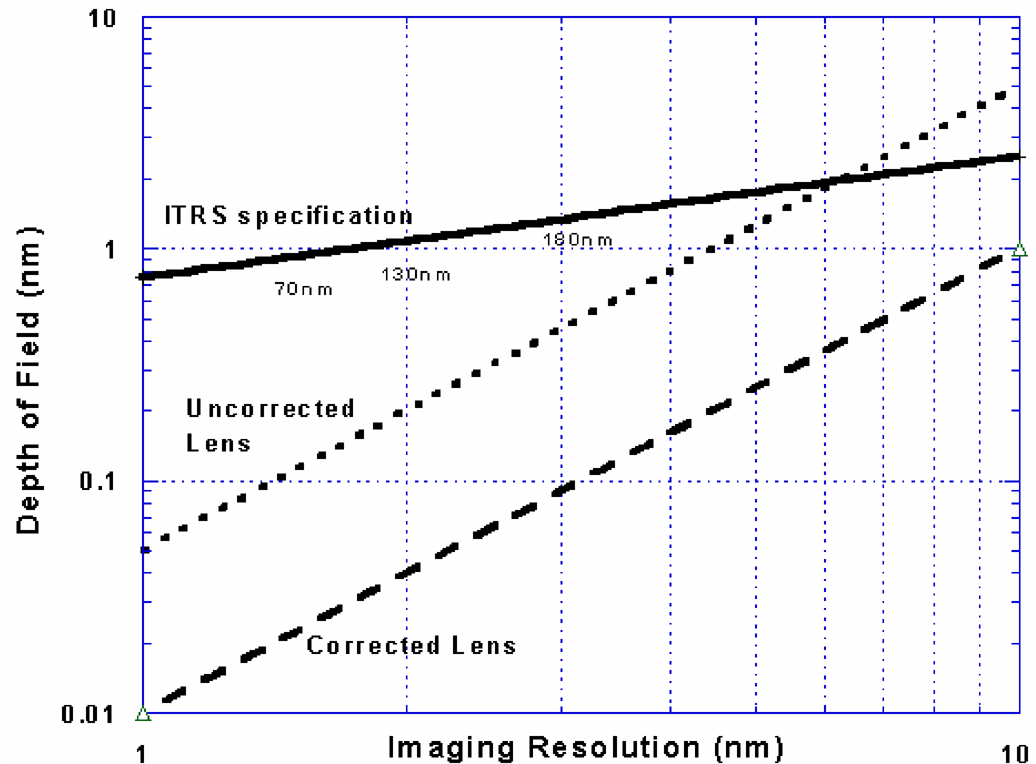
This needs New Technology- Aberration Corrected Lenses



It is now possible to **correct lenses for aberration**. This enhances performance and allows great flexibility in the design of the lens, stage, and chamber. Note that **the optimum NA is higher**, so the (diffraction limited) probe size is smaller, and much more beam current is available in the probe ($I_B \sim NA^2$) for the same gun brightness.

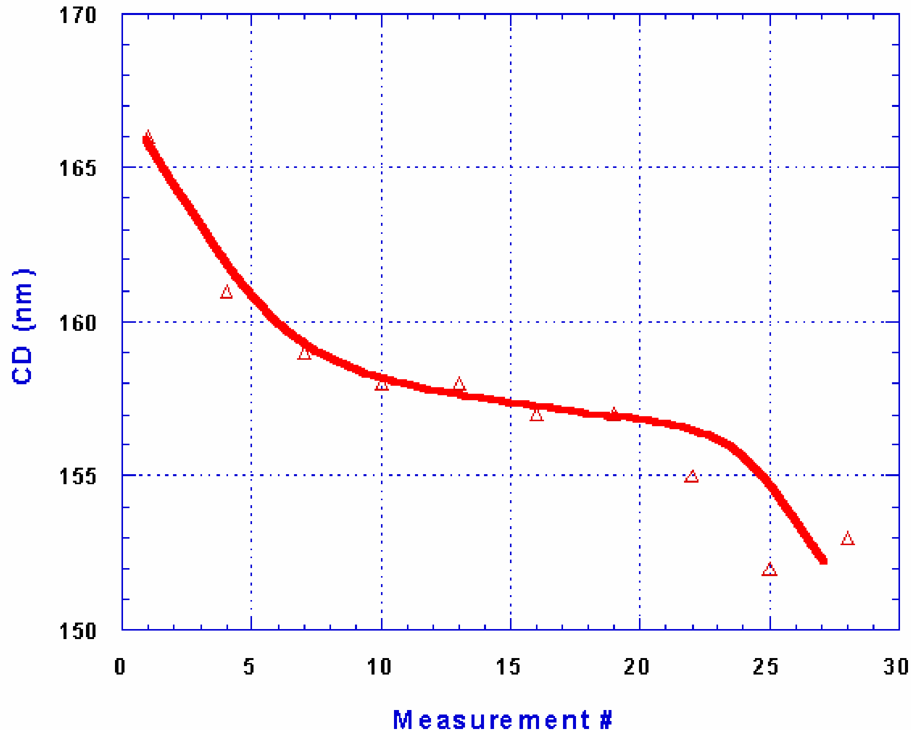
But ... Depth of Field ?

- The image depth of field depends on the spot size divided by the NA of the lens
- Even with present lenses the DoF is too small for comfort
- Reducing the spot size and increasing the NA results in a DoF which is only a few nm. A through-focal series may be required for metrology purposes



Adapted from M Sato, F Mizuno, EIPBN 2000

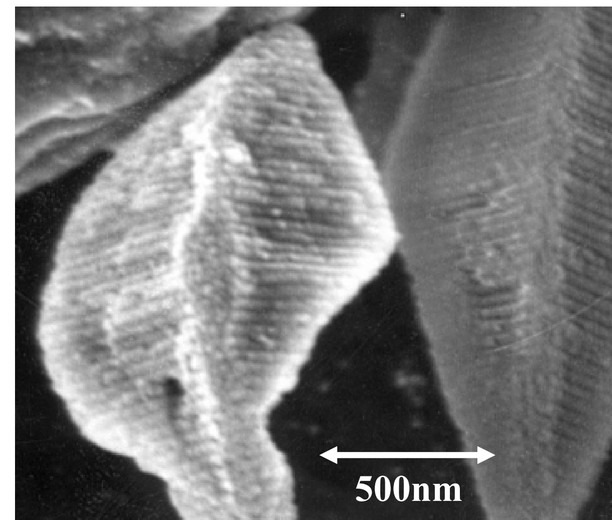
Unwanted beam interactions



Shrinkage of 193nm resist with dose

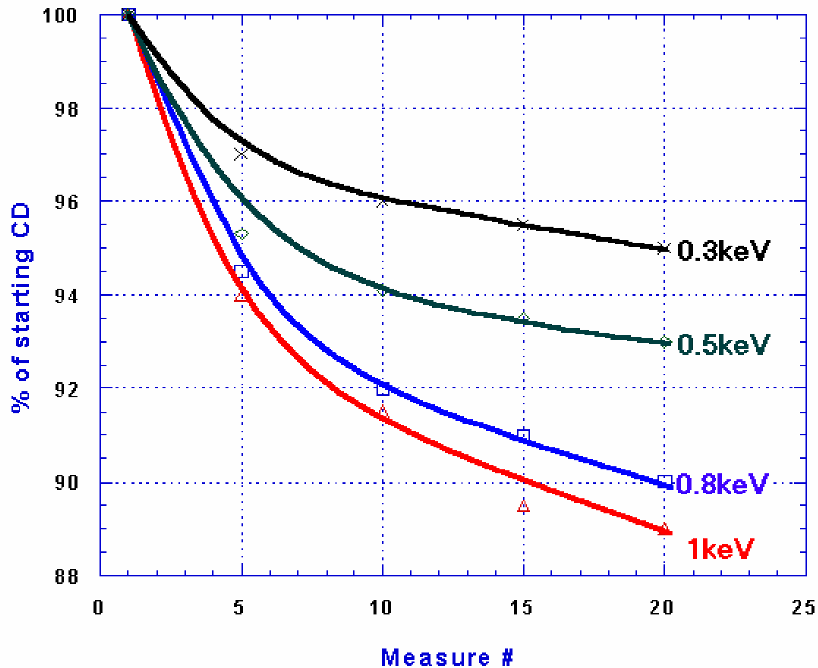
Su et al Proc. SPIE 4344, 2001

- 193nm and 157nm resists are highly sensitive to damage from the electron beam
- The changes observed are very large compared to desired precision and accuracy



Effect of 0.01μC/cm on protein protoxin

This needs new technology- Ultra Low Voltage operation



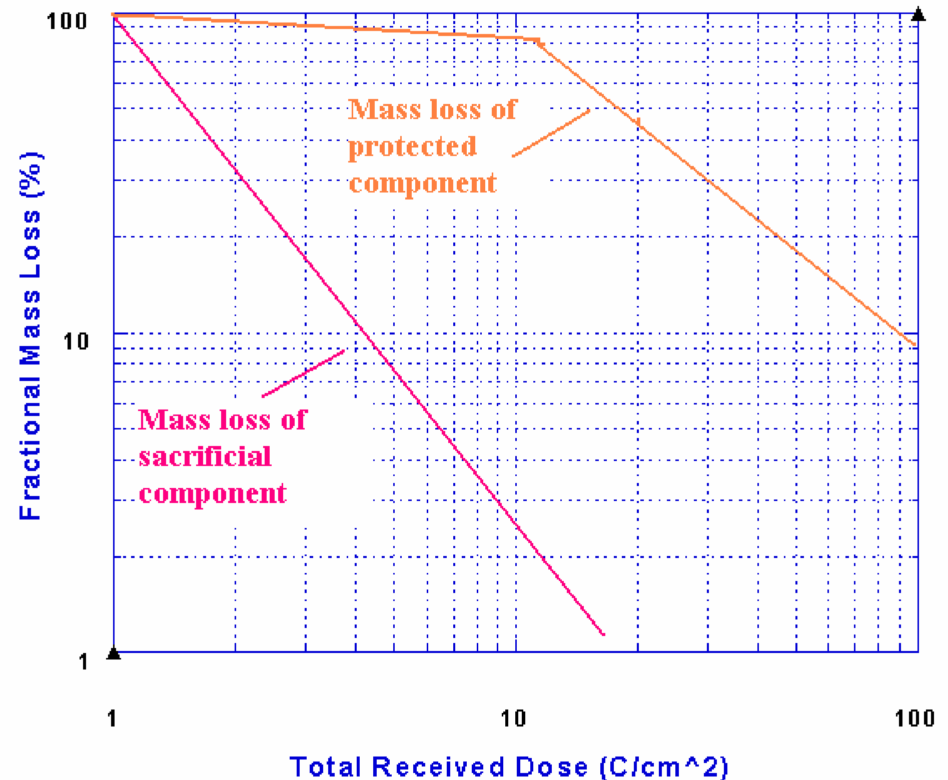
CD shrinkage in 193nm resists

Adapted from Su et al. SPIE ML Proc. 4344, (2001)

- **Damage can only occur within the beam range - which falls as $E^{3/2}$ - so lowering the incident energy to 100-300eV would much reduce the fraction of the target affected by damage**
- **Theoretically for low enough energies (<30eV) radiolysis might even disappear completely**
- **But the electron optical problems of operation at these UL energies are severe**

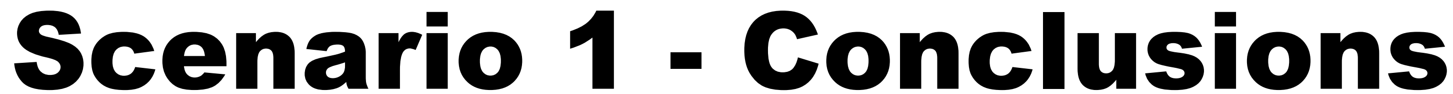
...or

- Radiation damage is tranmsitted by excitons which can redistribute energy over distances of ~10nm
- If they encounter a target of high damage cross-section they transfer their energy to that rather than to the sample of interest
- So infiltration of sample with sacrificial species leads to limited protection against radiation damage
- *Another job for resist chemists?*



Radiolysis of cell membrane in frozen glucose (sacrificial component) 200keV beam

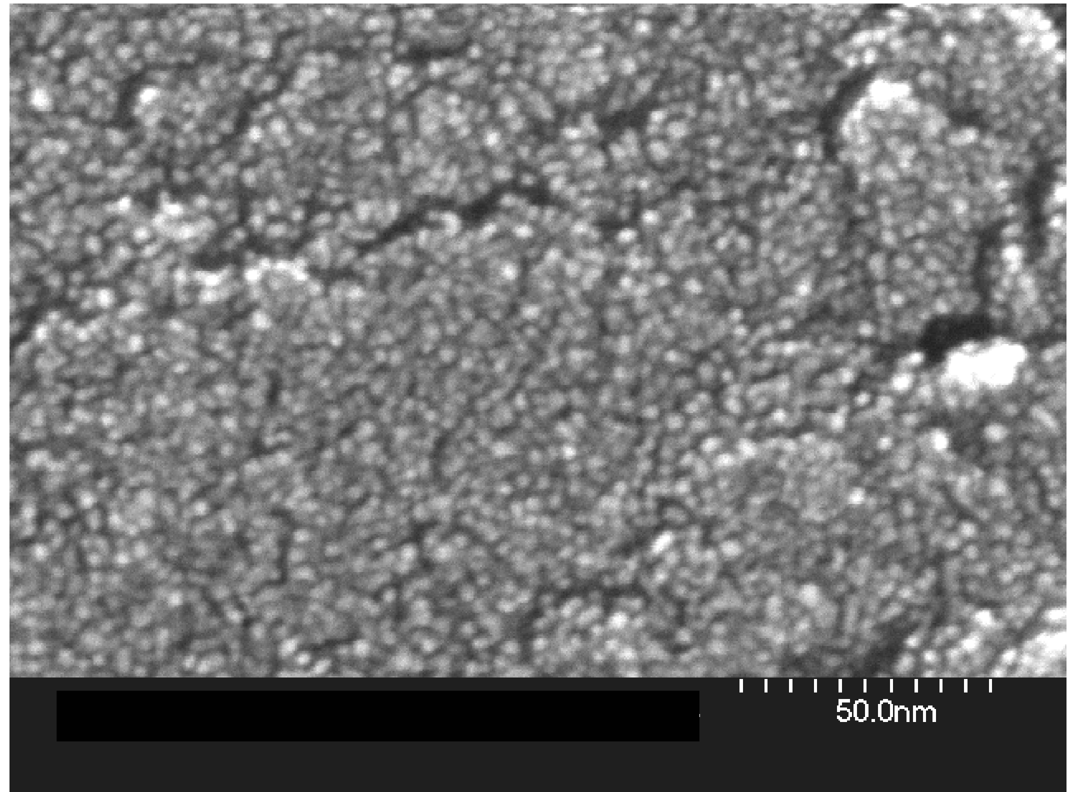
Scenario 1 - Conclusions



- Follows conventional wisdom and has momentum behind it
- Significant amounts of new technology are required. Takes time and money
- The amount of “upside” performance gain may not be large because too many conflicting factors are involved
- Fundamental problems (e.g. diffraction) cannot be engineered away

Scenario #2 - High Energies

- Given the problems of ultra-low voltage operation it is time to be counter-intuitive and go up in beam voltage
- An immediate benefit is that operation at high energies rapidly reduces the minimum probe size which varies as $C_s^{1/4}\lambda^{3/4}$ e.g. even at 30keV a probe size of less than 1nm is easily obtained with current lenses



SE image of platinum on Si at 30keV

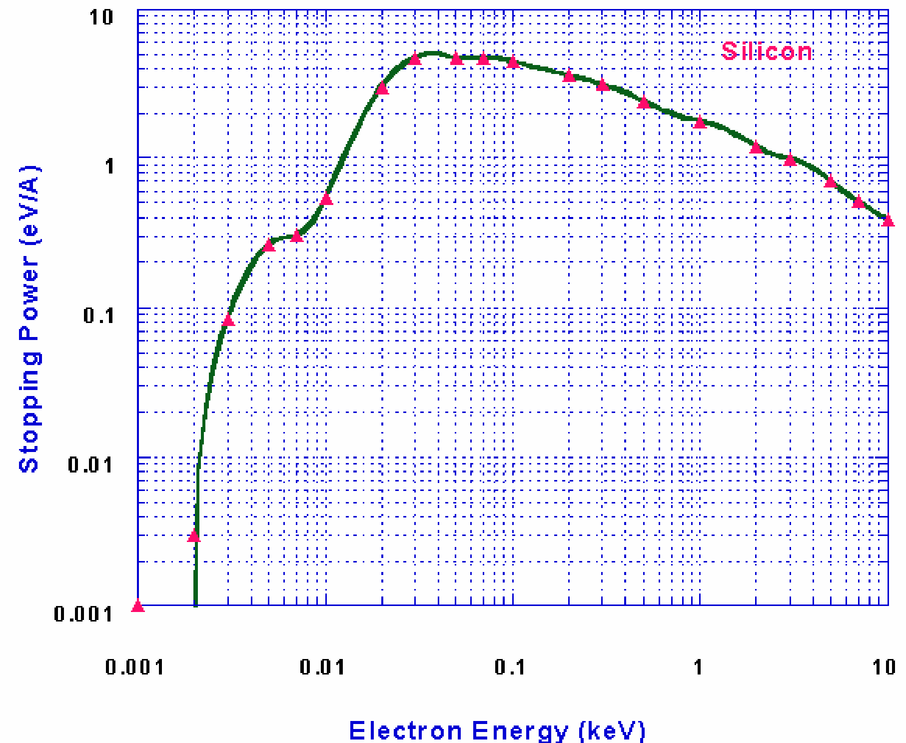
Courtesy Dr. B Tracey, AMD

Other advantages of a HV CD-SEM

- **Significantly higher brightness (30x to 200x that at 1keV) is available from existing sources *without the need for new technology*. Stable, long-life Schottky emitters can replace cold FEG sources without any loss in resolution due to the increased energy spread**
- **The column is less susceptible to external EM interference**
- **Contamination and surface coatings have little effect on the image**
- **Because the electron wavelength is much smaller at higher energies diffraction limiting is reduced and so an acceptable depth of field can be achieved**

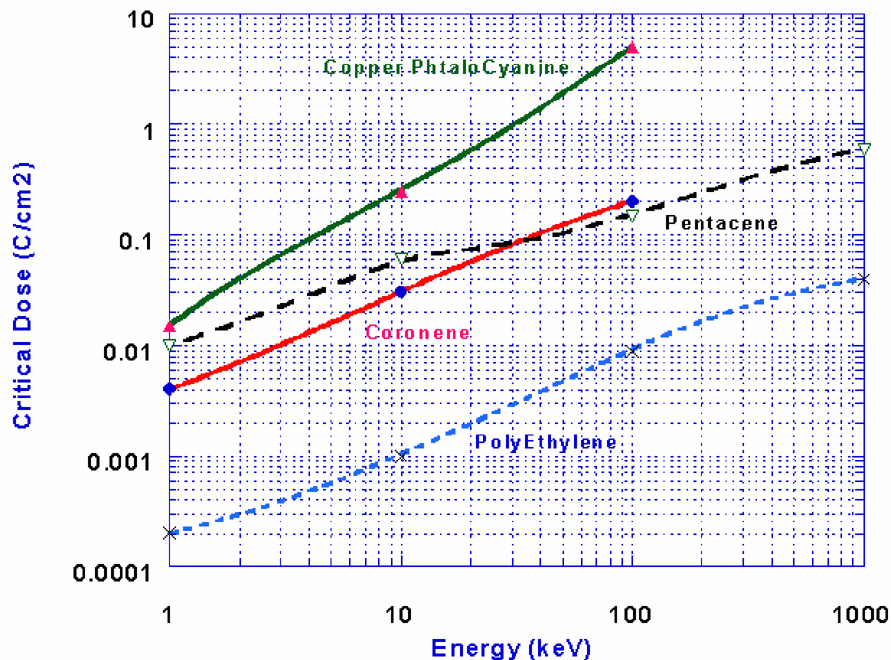
Why be afraid of high voltage?

- The usual misconception is that low energy electrons damage less than higher energies but the SP is at a maximum at "low" operating energies and falls steadily with increasing energy
- As the energy is increased the total energy increases as E, but the volume rises as E^5 so the energy per unit volume falls as about $1/E^4$
- Because the beam range is now much longer than the feature size, damage is mostly deposited in the substrate



Experimental Stopping Power Data for Silicon

Radiation Damage vs Energy



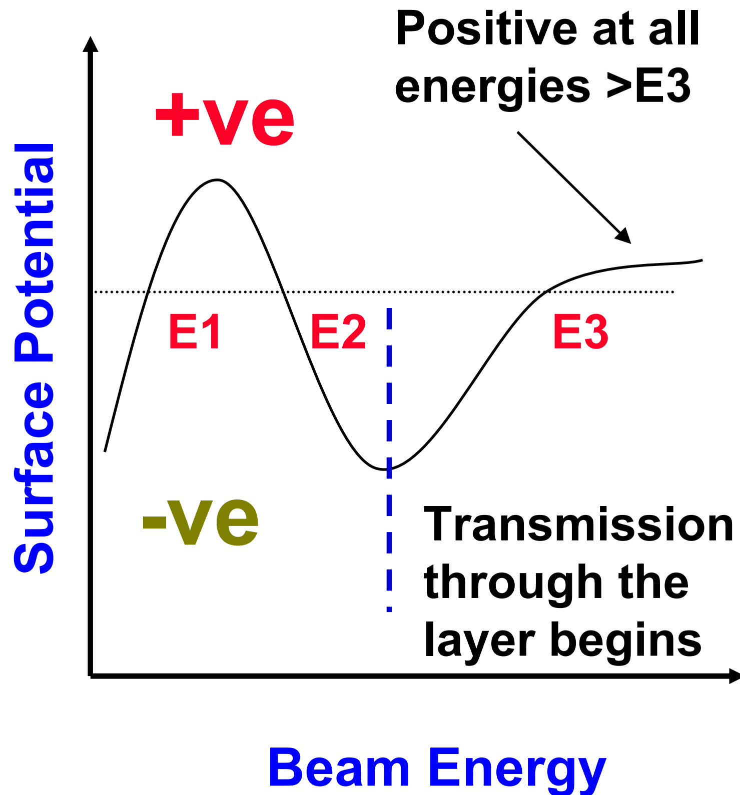
Experimental measurements of critical beam dose to destruction for organics/polymers

- This is supported by experimental data on radiation damage in organics and polymers
- As the energy goes up the dose (C/cm^2) required to terminally damage the material is seen to rise rapidly. This should translate into less swelling or shrinkage for a given incident dose at high energies
- However at higher energies knock-on damage occurs (80keV for carbon, 220keV for Si). The optimum energy window therefore seems to be between 30 and 80keV

Gate Oxides - Threshold Shifts

- The other effect of beam irradiation may be threshold shifts as a result of charge implanted in the gate oxide.
- A detailed analysis of this effect, based on the published model of Hector et al. (SPIE Microlithography Proceedings 2001) shows that at 200keV, assuming a 3nm gate oxide thickness, and a beam dose of 10μC/cm^2, the threshold shift is below 10 millivolts - too small to be significant. This includes the direct contribution from the beam (electron-hole pairs) and the effect of charge implanted from X-ray fluorescence.
- By comparison at 1keV, and for the same beam dose, the shift would be 15 to 20x higher.

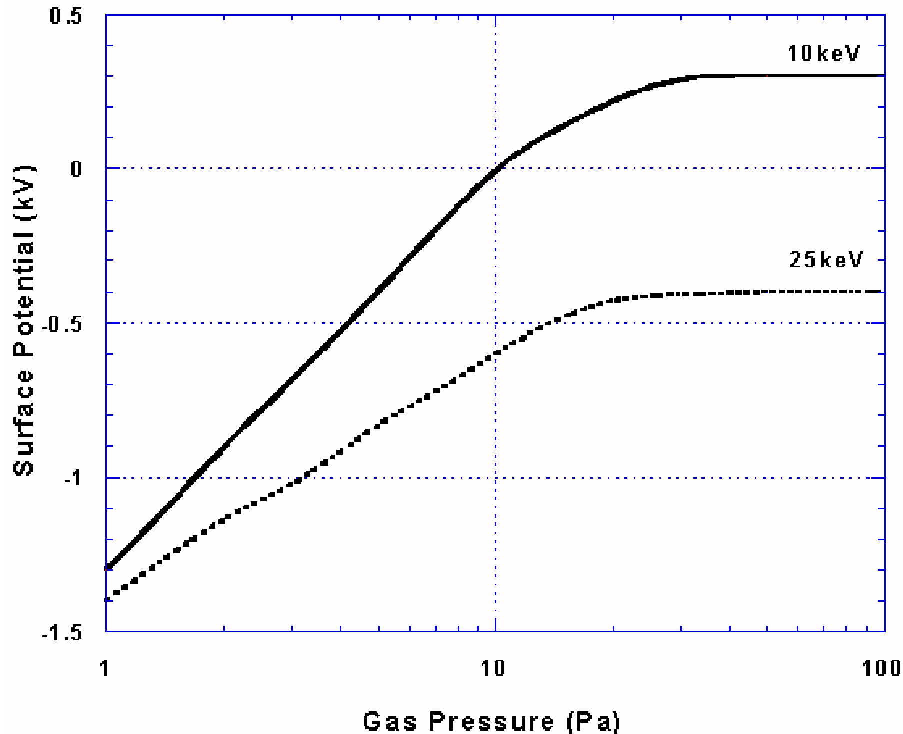
What about charging at high voltage?



Variation of charging with energy for insulating thin films on a substrate

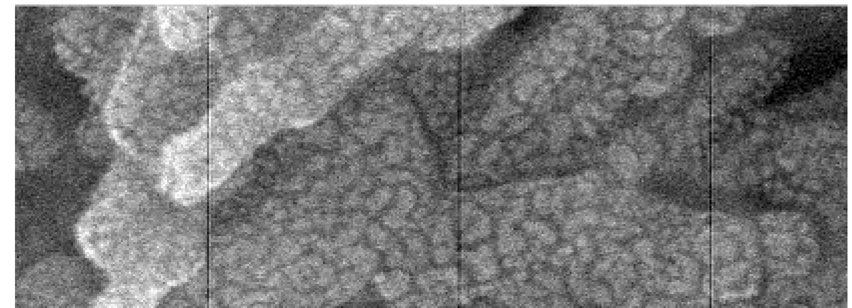
- The drive to low beam energies was motivated by the need to work at the E2 crossover to control (negative) charging
- *Charging distorts profiles and locally changes the magnification*
- For operation at energies greater than E3 the charging is positive and decreases with energy
- For many purposes this solution may be all that is required
- Otherwise an alternative exists...

Charging in a gas



- Surrounding the sample with a low pressure atmosphere of gas allows the charging to be controlled in a simple way
- This action is self controlling
- The gas does not limit high resolution performance

Experimental charging data for a EUV Cr on Glass mask. Air environment, 200pA current

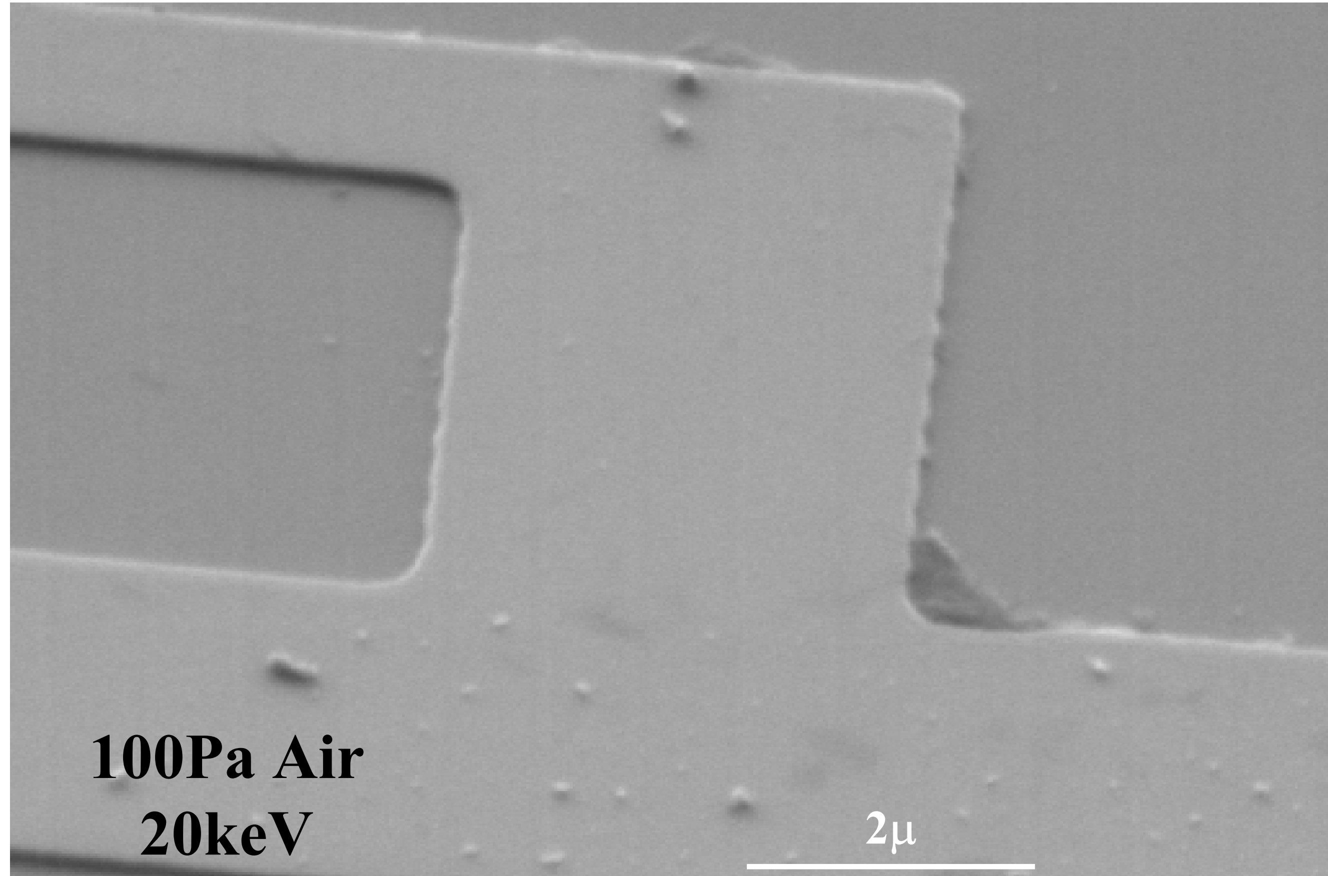


500nm

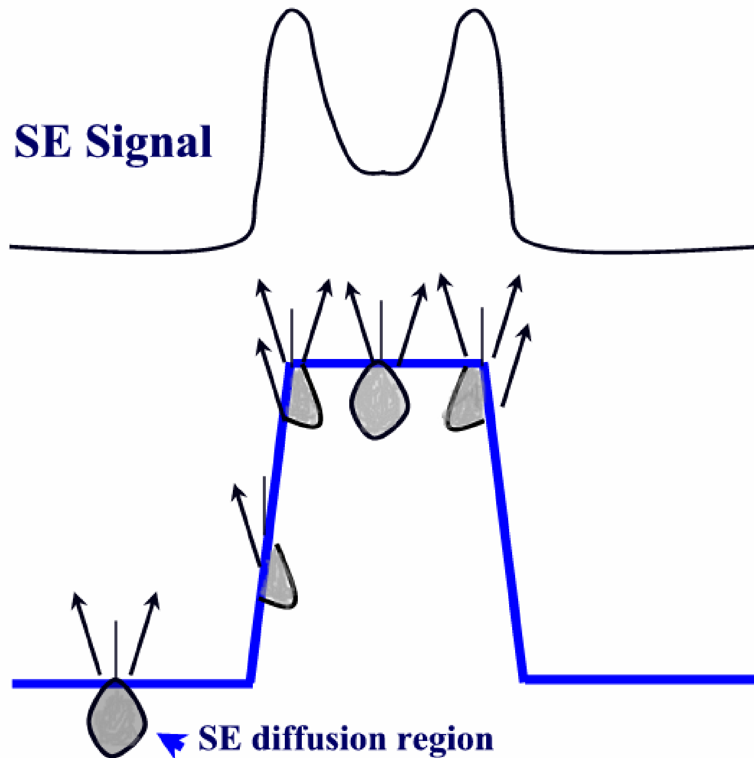
20keV image at 400Pa (3T) of air

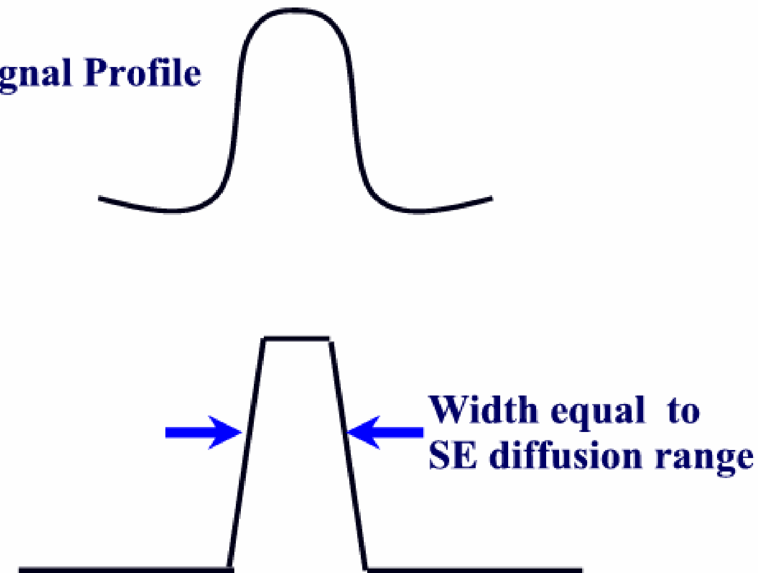
Gas Stabilized image of a binary Cr/Quartz mask

- ⌘ By adjusting key parameters - the beam energy, gas pressure, and the gas path length - the charging and contamination can both the eliminated as shown in the image



The problem with SE

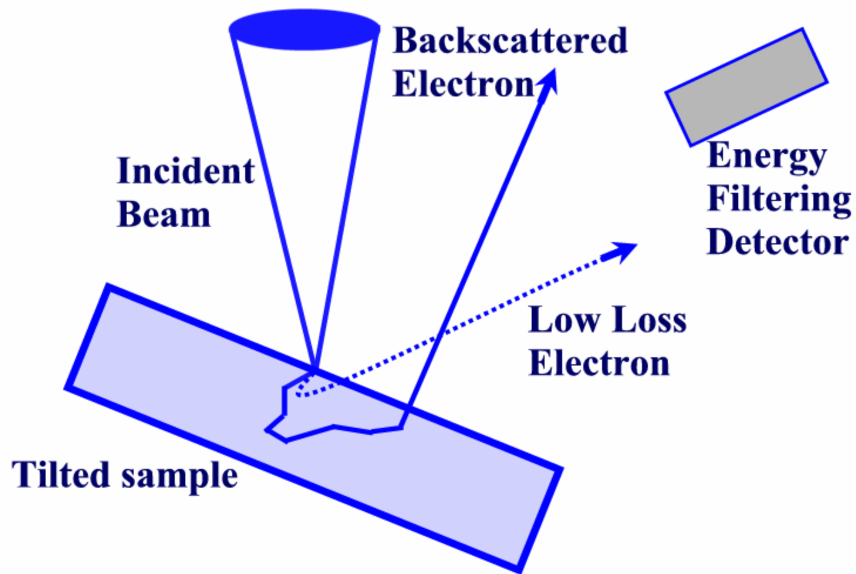




The diffusion of SE over a range of a few nm creates the 'edge bright line' effect

As a result when the feature size is close to the SE diffusion range the object is not resolved. This occurs in the 5-10nm range for resists

A solution - Low-Loss Imaging

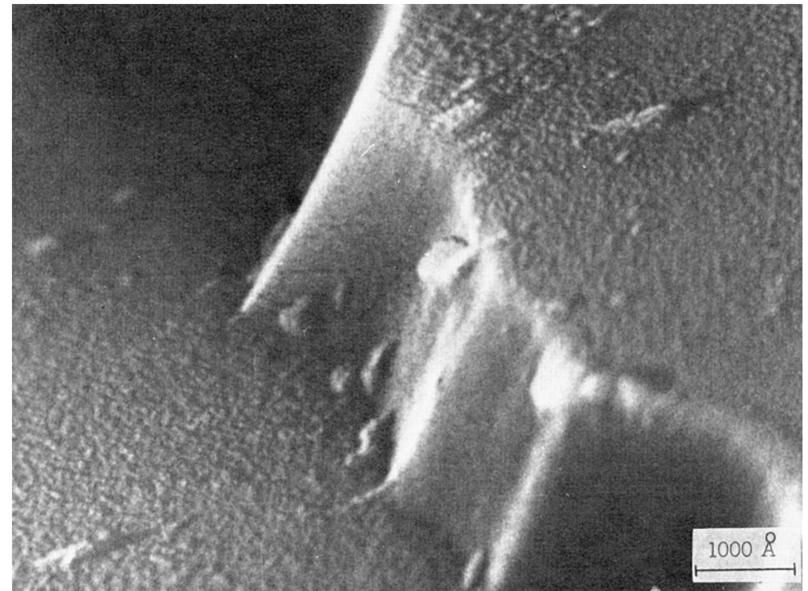


Low Loss - Wells and Broers 1970

- Low-loss imaging uses BSE electrons that have lost less than a small % of their energy
- Since the stopping power is about 1eV/nm these low loss electrons can be guaranteed to have only traveled a very short distance in the specimen
- Single high angle scattering event also guarantees a small impact parameter (<0.01nm) and hence high resolution
- Unaffected by charging, and contamination. Good for overlay?

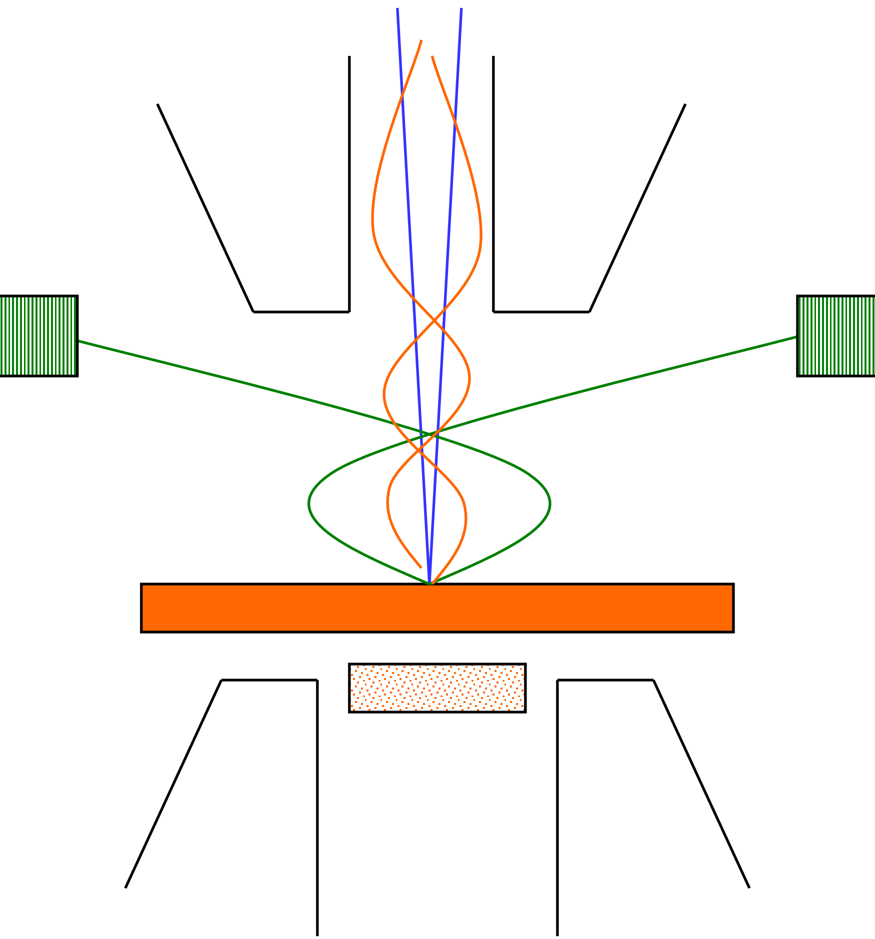
Low Loss Imaging

- Low loss imaging offers very high resolution and much better contrast than the SE image. Well suited to high performance metrology
- But..............
- The electrons must be energy filtered to remove inelastic components
- The original geometry for low loss requires a high tilt, and restricts operation to the edge of the sample



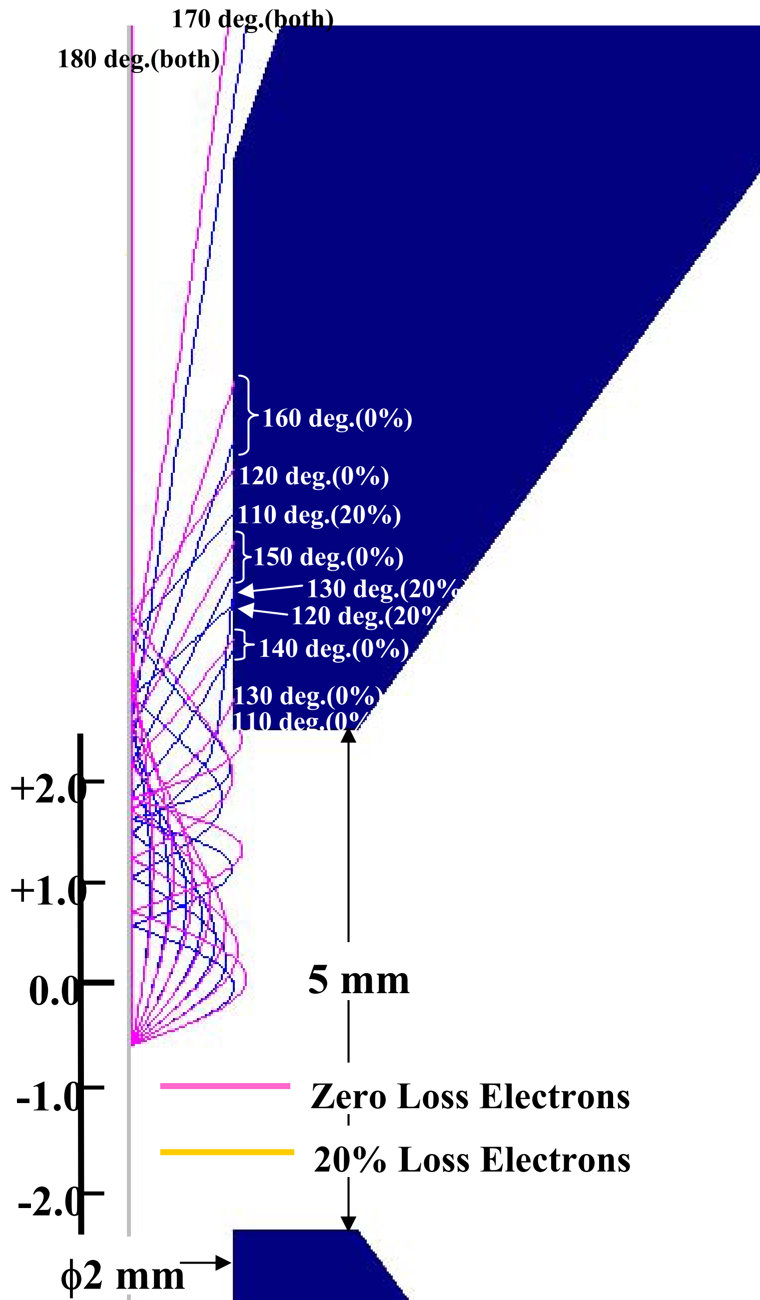
Low loss image of a step in amorphous silicon

New geometry for Low Loss



- By using novel lens designs including permanent magnets the low loss electrons can be selectively focussed on to an annular detector. Lower energies electrons and SE go back through the bore.
- This could permit normal incidence viewing across a whole wafer
- Poorer - but still adequate - energy resolution

Trajectories of Zero & Low Loss(20%) Electrons



Excitation Parameter		26
	V_{acc}	200 kV
	Coil Turn 926T x 2	
	Current	6.36A

Specimen Position -0.65 mm

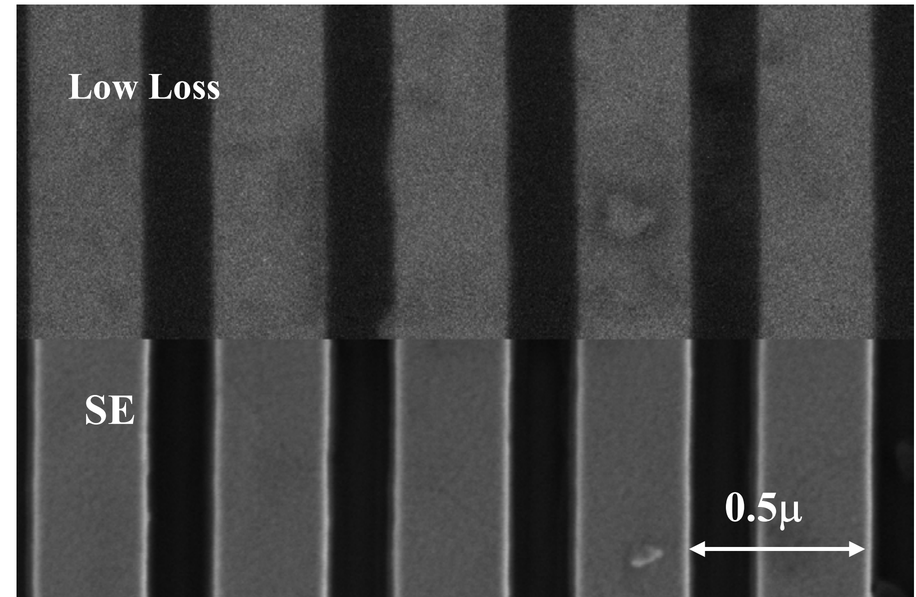
(the origin is at the center between both pole pieces)

Maximum B field Position		
	Upper Pole Piece	+1.5 mm
	Lower Pole Piece	-1.5 mm
B-field Strength		
	+1.5 mm (Max.)	1.73 Tesla
	±0 mm	1.68 Tesla

Electron optical conditions to achieve this type of operation have now been calculated for several instruments. The example shown is for a 200keV STEM system

Low Loss operation

- The predicted conditions for the new Low Loss geometry have been demonstrated to produce good quality images
- The LL signal to noise ratio is lower than desirable because of limitations in the detector
- The comparative images show that the familiar artifacts of SE imaging (the edge brightness effects, charging) are absent and edge definition is enhanced



A resist structure recorded in Low Loss mode using the new geometry, and the corresponding SE image. 5keV operation, Hitachi S4300SE

Scenario #2 - Conclusions

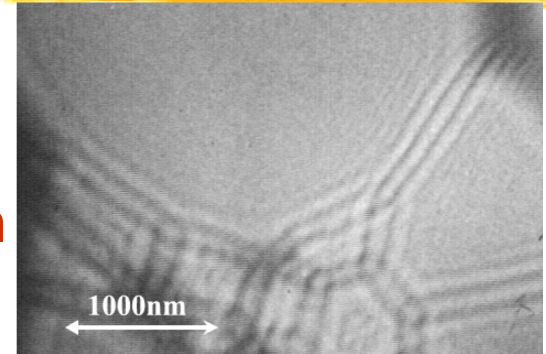
- The high energy CD-SEM is counter to conventional wisdom and current practice
  - No new technology is required - could be a relatively cheap and quick process
  - Significant upside available
  - Direct view overlay metrology
  - Pro-active solutions to the problem of charging, damage, and limitations to SE imaging
  - Questions about radiation damage and charging will require detailed study

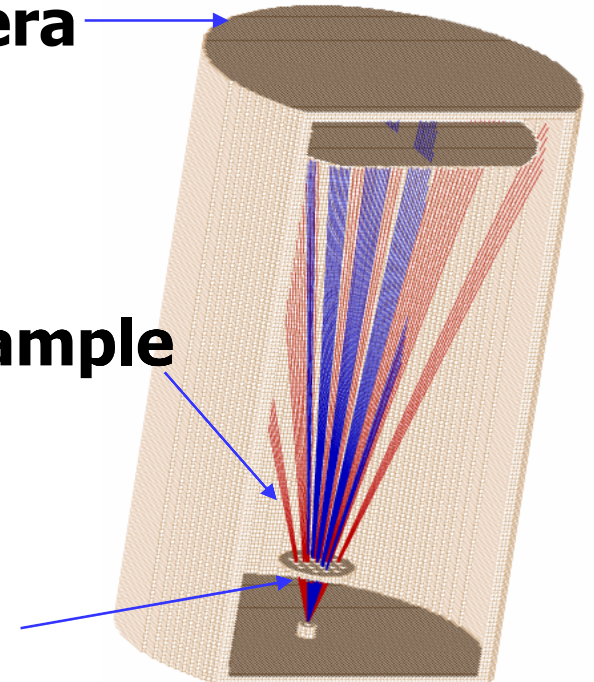
- If the problems inherent in SEM-based imaging systems cannot be solved in a generally acceptable way then other avenues must be tried.
- Methods such as scatterometry offer high precision and rapid analysis, but at the expense of the ability to make site-specific measurements
- Probe based techniques (AFM) - offer true 3D analysis but are relatively slow, require correction for tip shape and tip wear, and are challenged by many geometries
- Holography - optical or electron-optical - can offer high precision, three dimensional detail, and both statistical and site-specific data

Holographic techniques

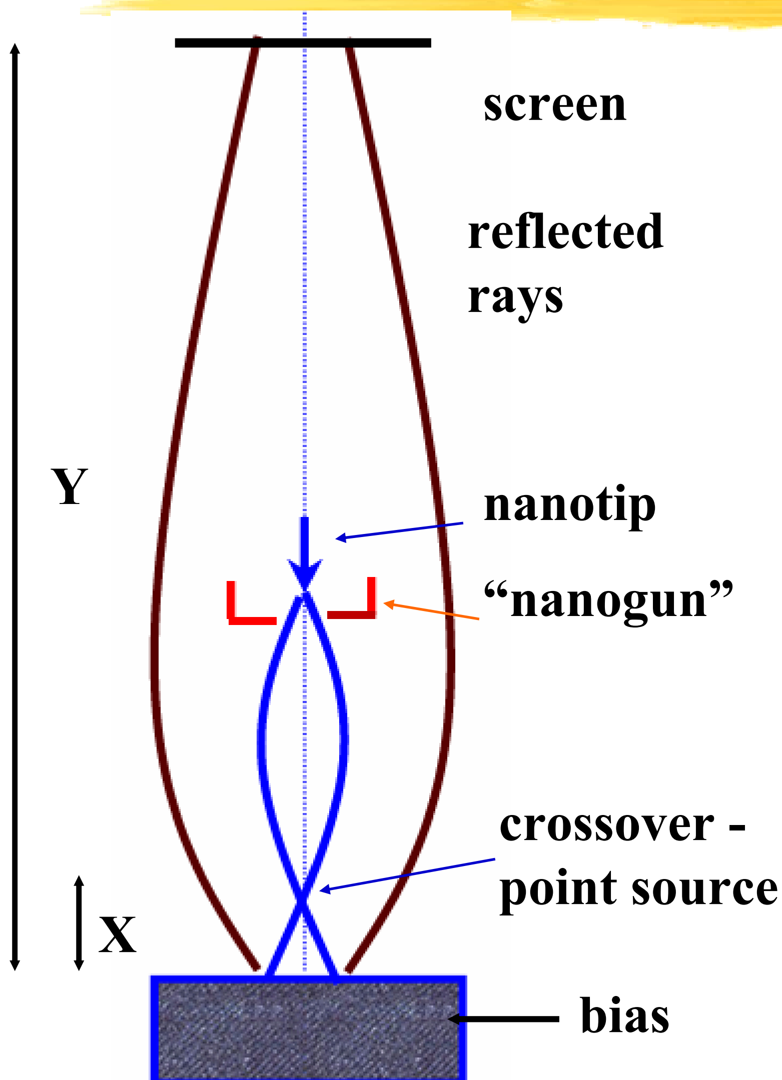
- The simplest tool is the Point Projection Microscope (PPM) which uses a nanotip field emission source
- This has no imaging lenses and so is not constrained by aberrations, or diffraction
- In transmission mode the PPM has been shown to produce Fresnel holograms with nanometer resolution at energies below 300eV

Fresnel hologram





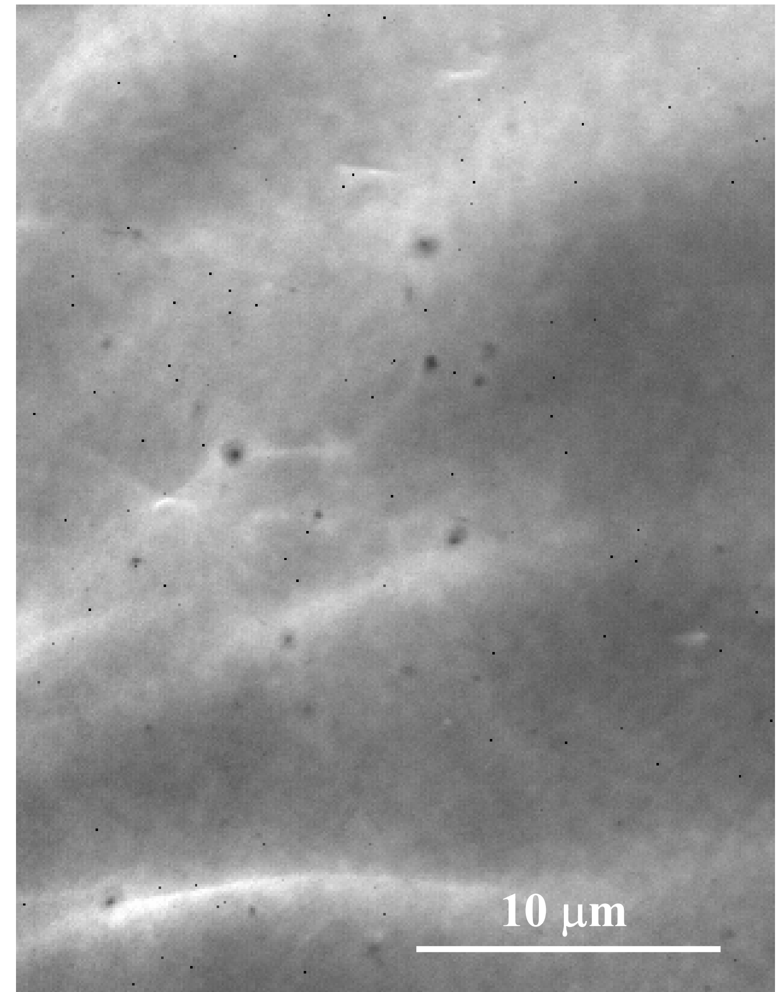
New PPM Reflection Geometry



- The system has now been configured to produce vertical incidence and reflection
- The nanotip emitter no longer uses the sample as an anode. Instead a self - contained nanogun has been developed
- The sample potential can now be varied around zero to provide a variety of imaging modes including 'mirror' operation

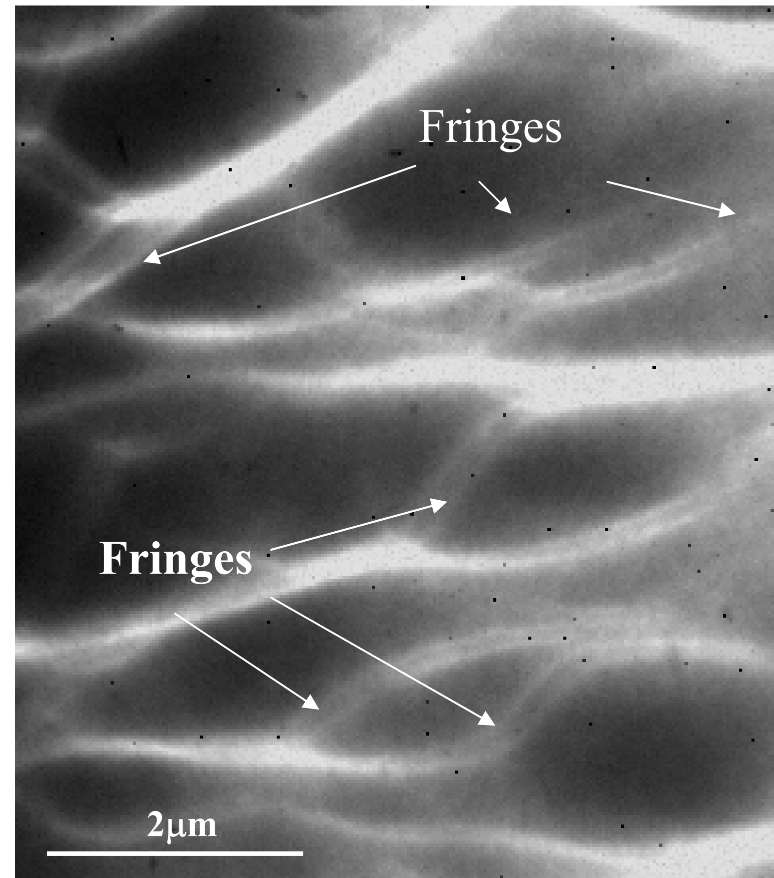
Reflection PPM Images

- We are now generating useful reflection images of a variety of bulk samples demonstrating good resolution at beam energies below 1keV
- The example shown here was recorded at 500eV energy. The image shown is from a single TV frame and displays excellent surface detail at high contrast from the metal foil sample
- Control of charging remains a problem on poor conductors



Holography in reflection PPM

- Most importantly we have now succeeded in generating Fresnel holograms from a bulk sample in reflection mode for the first time
- This demonstrates that the coherence and brightness of the nanotip emitter have been retained with the nano-gun while enhancing the versatility of the PPM
- The optimum conditions for fringe visibility have not yet been determined and it is often difficult or impossible to generate holograms on a given day



Reflection hologram obtained at 500eV with an integration time of 100millisecs