



Technologies pour la Microscopie Electronique à Balayage de résolution sub-nanométrique à haute et basse tension

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Paris, 2 Déc. 2010

GN
MEBA



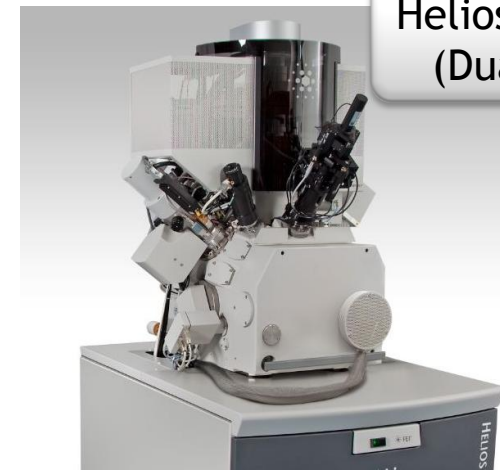
**Réunions
pédagogiques**

*"Colonnes électroniques et ioniques -
DéTECTEURS spécifiques associés :
Etat de l'art présenté par les constructeurs"*

SEM Extreme High Resolution (XHR)

What is it? What are the values?

- **Extreme High Resolution (XHR)**
 - Sub-nanometer resolution from 30kV down to 1kV
- **XHR values as implemented**
 - Better **Resolution**
 - No resolution dependence on kVs
 - Take better advantage of **low kVs**
 - Surface sensitivity
 - Less beam damage / charging
 - More **Contrast**
 - FEI 2010 Detection & Imaging
 - Traditional SEM **flexibility & ease of use**



Helios NanoLab
(DualBeam)



Magellan (SEM)

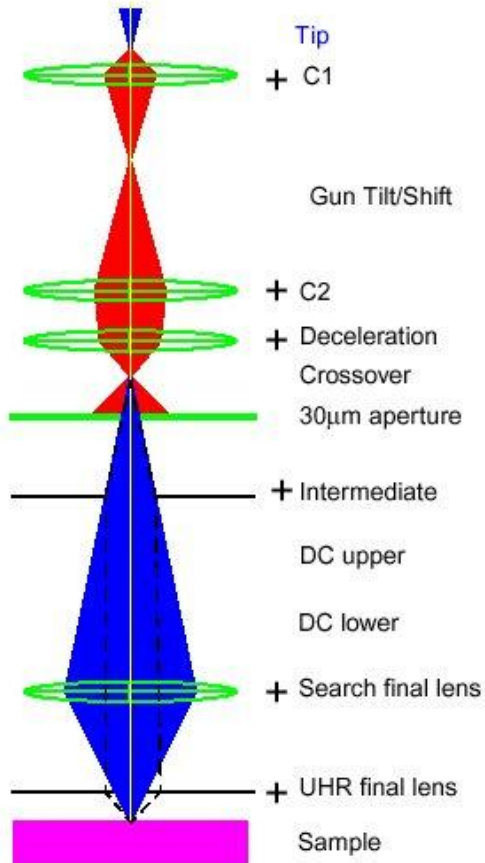
Helios NanoLab et Magellan

Technologies de la colonne MEB et de ses détecteurs SE/BSE

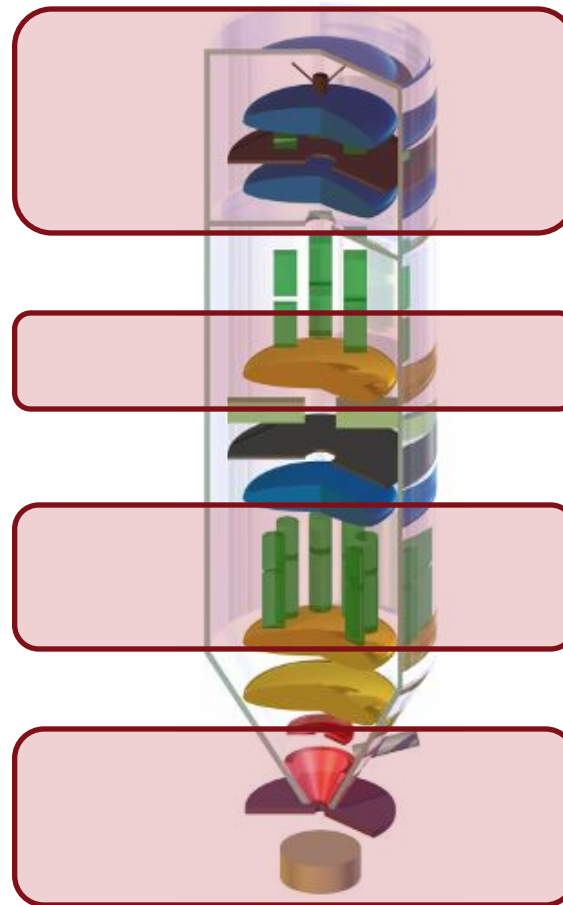
1. La colonne Elstar™: optique générale et choix technologiques
2. Le monochromateur de la colonne Elstar
3. Le détecteur in-lens (TLD) : principe, optimisations récentes et possibilités de filtrage
4. Le détecteur DBS: technologie, principe et possibilités de filtrage

XHR SEM - Key Technology Ingredients

The Elstar™ electron column + FEI 2010 Detection & Imaging



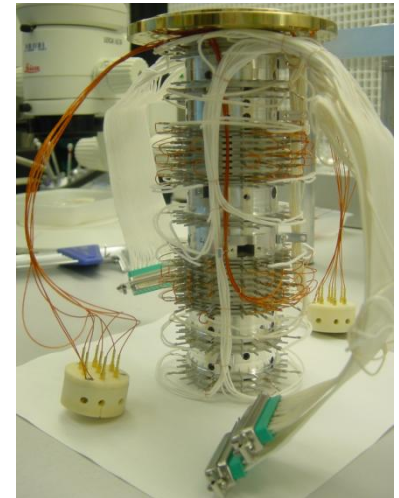
Elstar - general optics



Elstar + FEI 2010 Detection & Imaging specificities

How to improve further SEM resolution?

- Aim: better resolution at low kV's (≤ 2 kV)
- \rightarrow limiting contribution: chromatic aberration $\sim C_c \cdot \Delta U / U$
 - ~~Correct lens aberration C_c ? \rightarrow C_c -corrector needed: complex and costly mechanics/electronics/software~~
 - Decrease ΔU ?
 - \rightarrow using cold-FEG: ~~less stable and less max current than Schottky FEG~~
 - \rightarrow using monochromator: can we maintain versatility of the column?

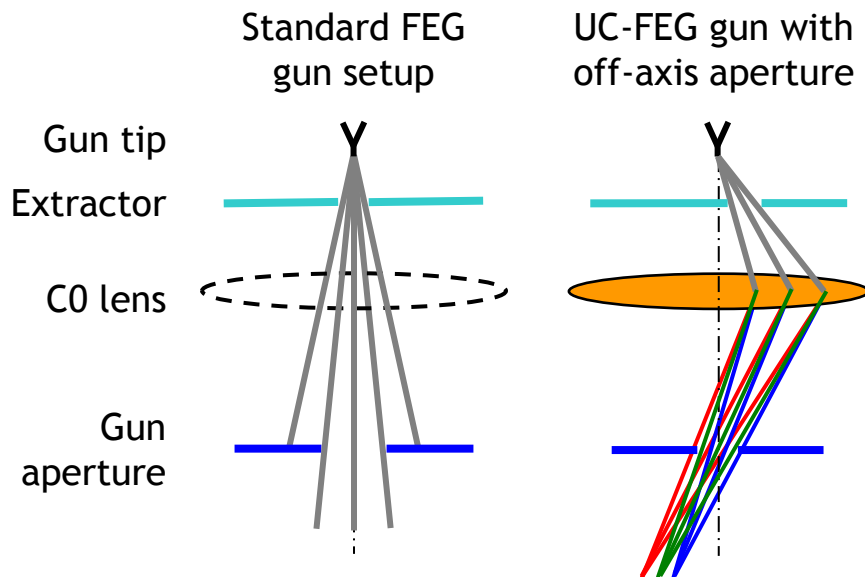


SEM Corrector

The Elstar UC Gun

Principle and energy spread improvement

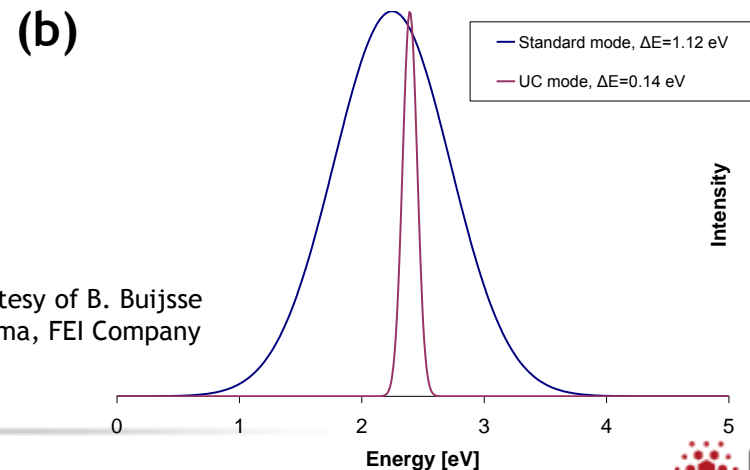
Standard FEG vs UC-FEG gun design



Energy spread: (a) reported and (b) UC measurement using biased faraday cup

- Measured UC FWHM energy spread 0.15 eV
- Experiment matches theory

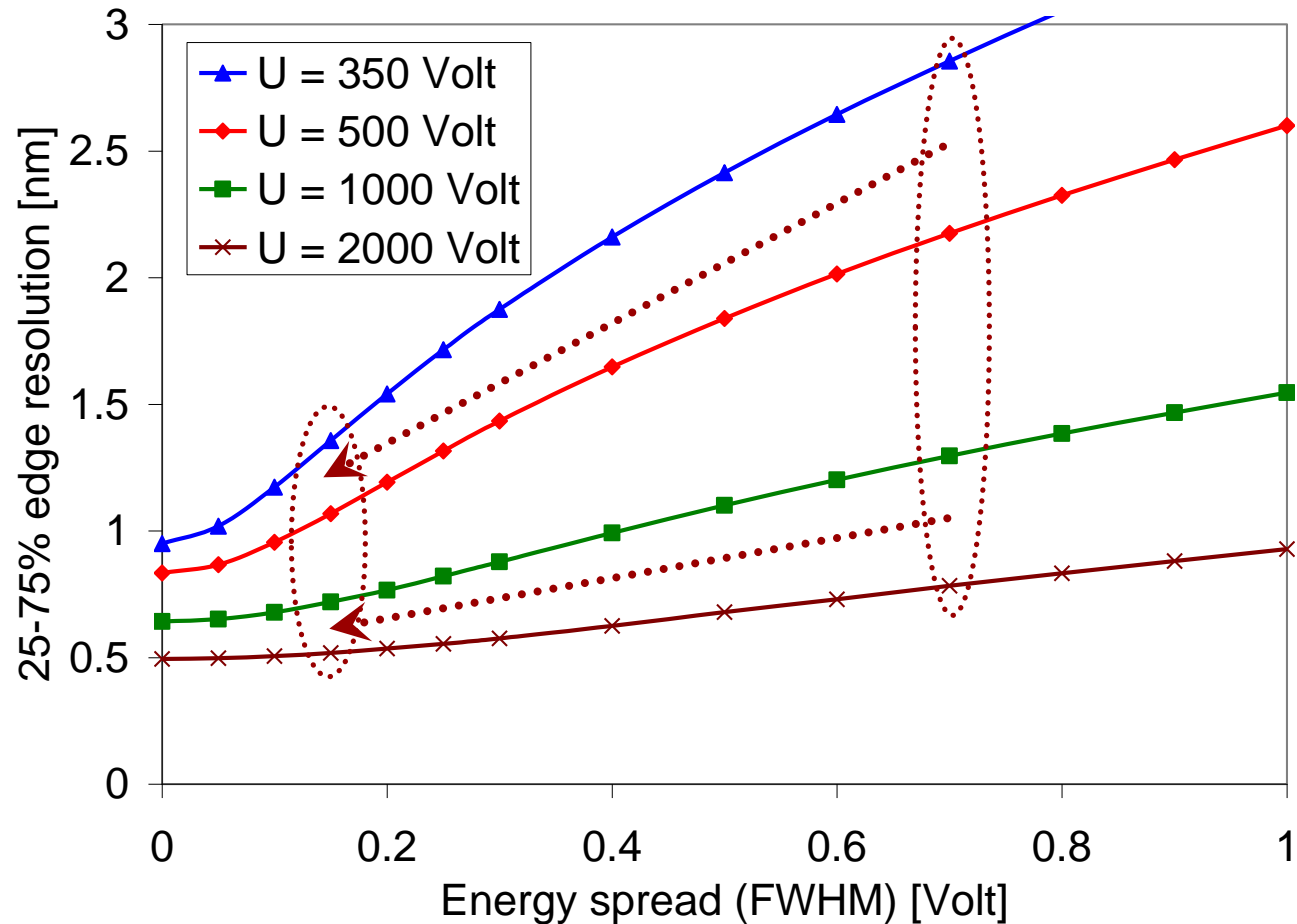
(a) Gun technology	Energy spread
Schottky	0.5-1.0 eV
Cold Field	0.25-0.35 eV
Schottky-UC	0.15 eV



Data courtesy of B. Buijsse and L. Tuma, FEI Company

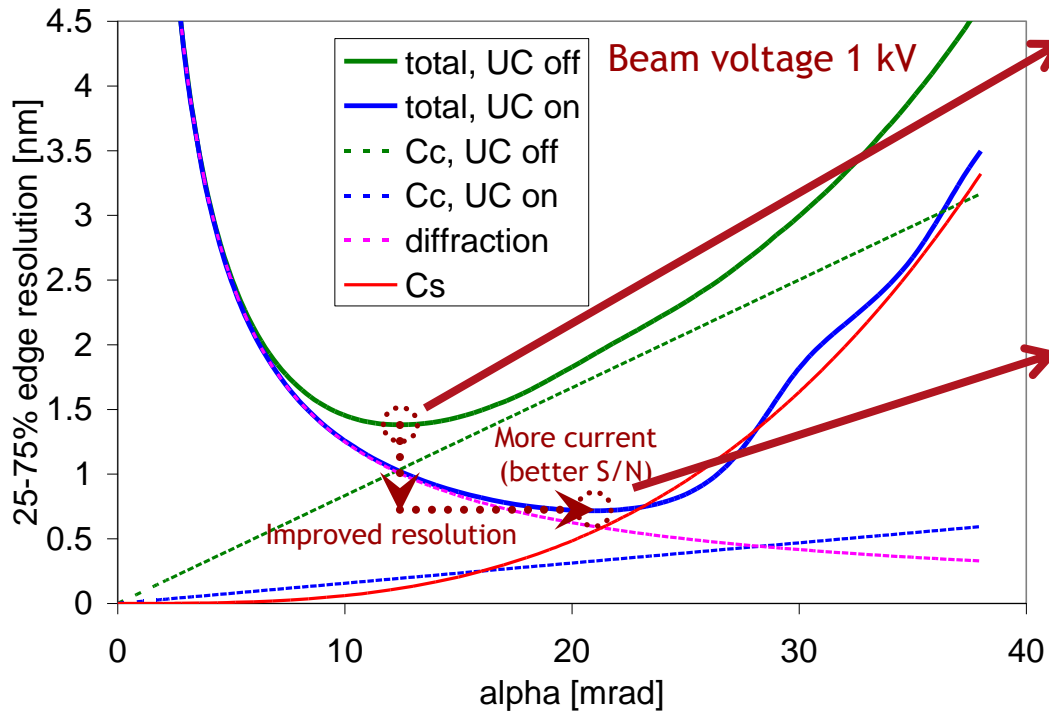
The Elstar UC Gun

Benefit of reducing the energy spread



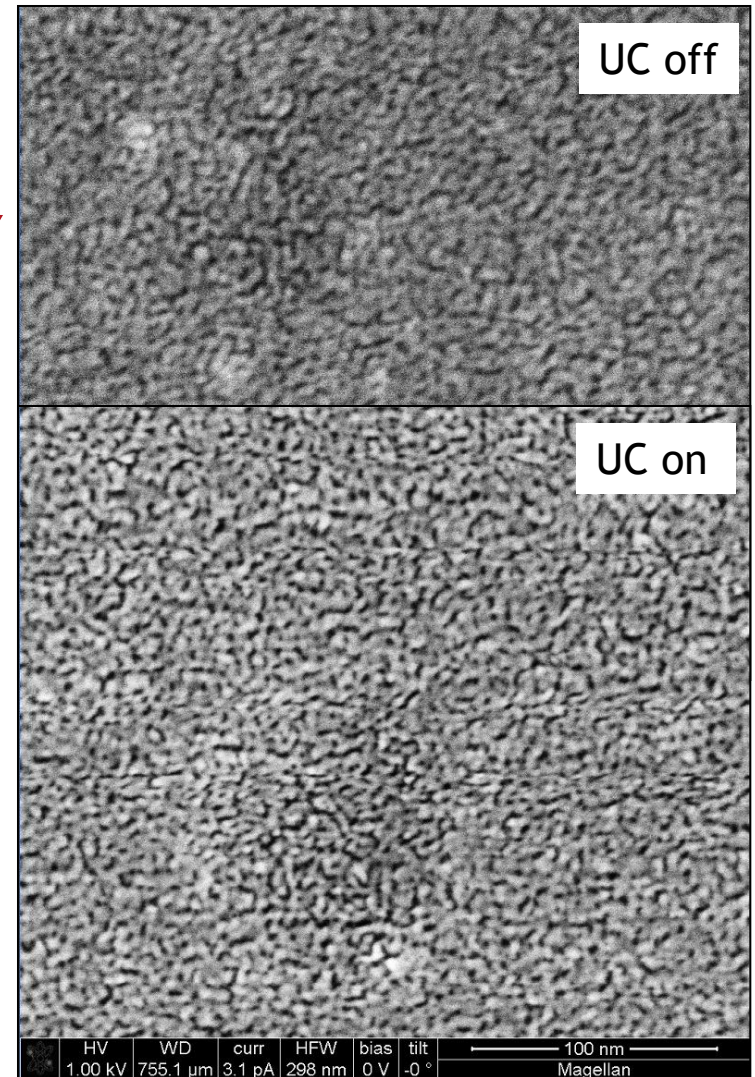
From: Young et al, SPIE 2009

Performance improvement with monochromator



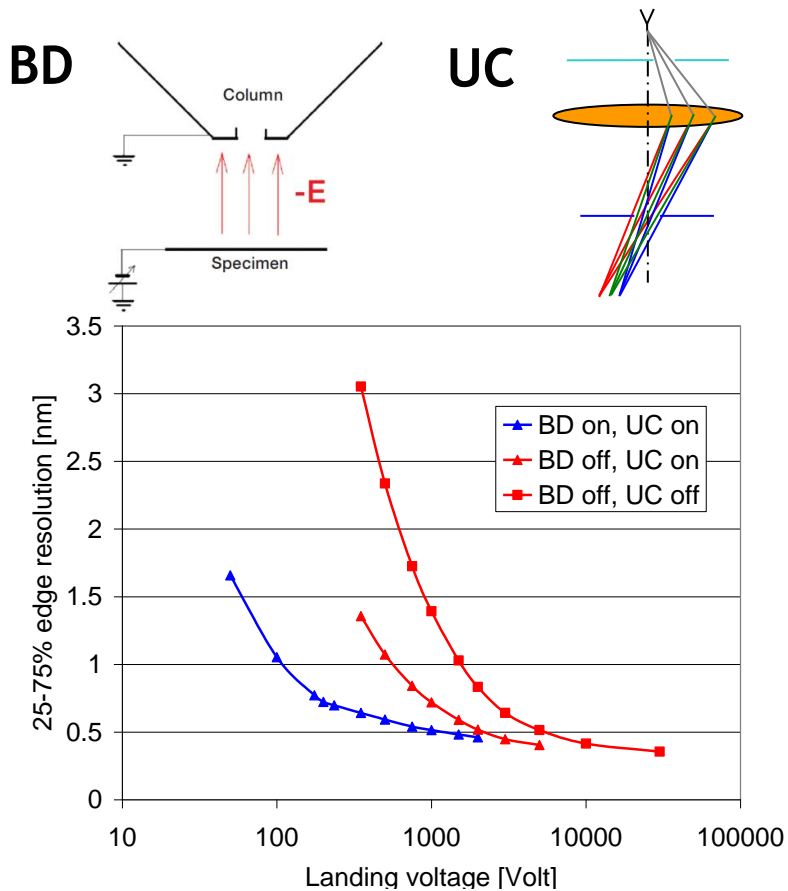
From: Young et al, SPIE 2009

From: J. Michael, D. Joy, B. Griffin, M&M 2010

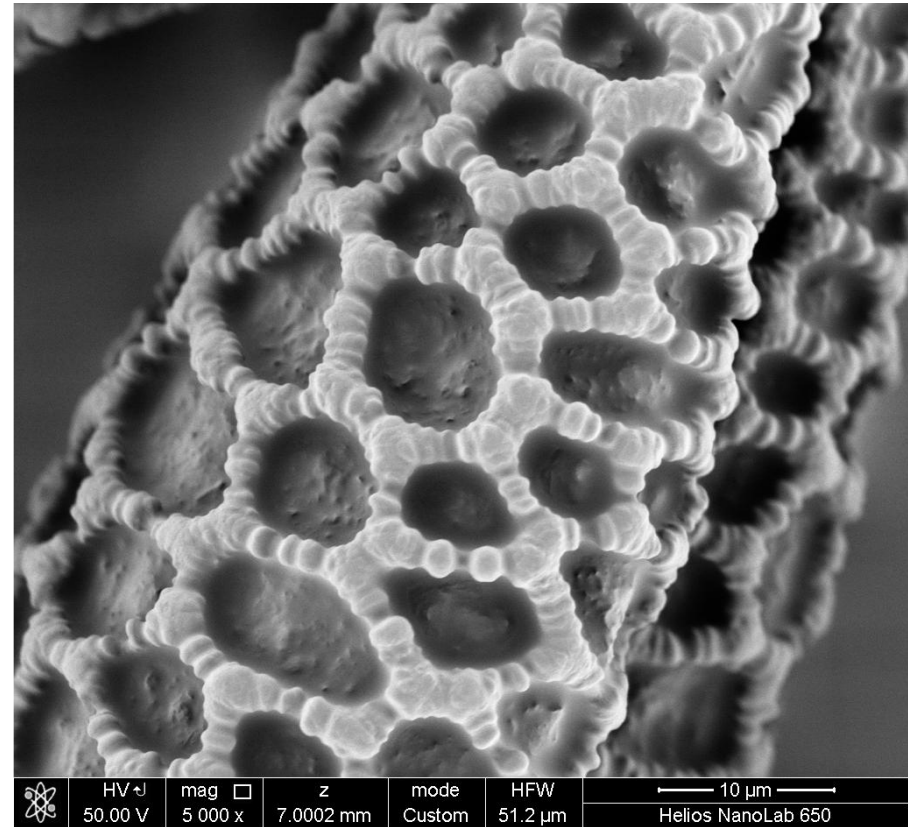


Beam Deceleration (BD)

Improving resolution & contrast - very low landing energies



Elstar column - influence of UC and BD
From: Young et al, SPIE, 2009



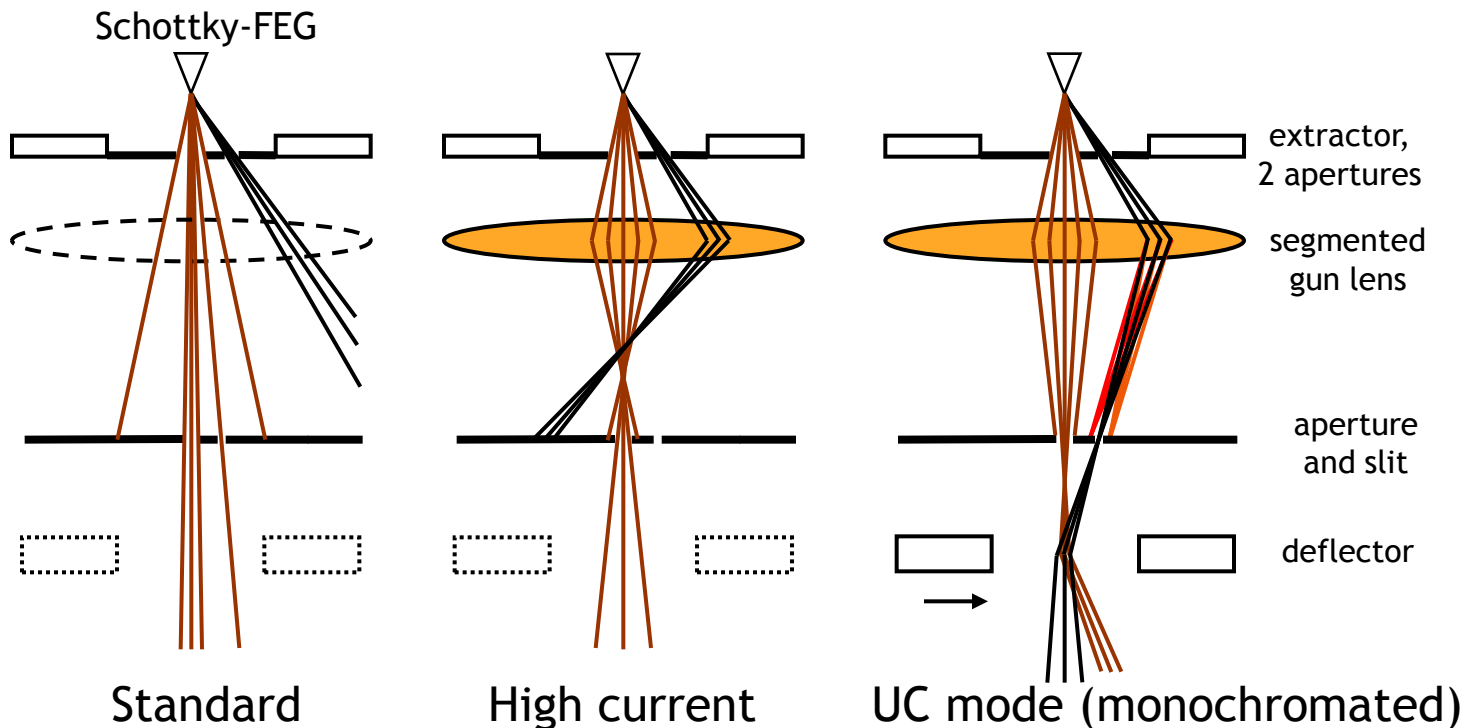
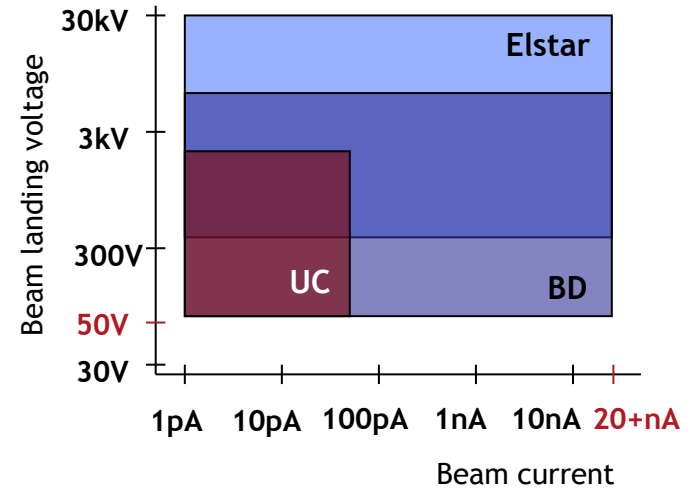
Uncoated Pollen
Images courtesy of B. van Leer & D. Wall - IMC17

The Elstar UC Gun

Preserving a large parameter space

3 beam modes

From: Henstra et al, M&M 2008 proc.



The Elstar UC Gun

Resolution as measured by users

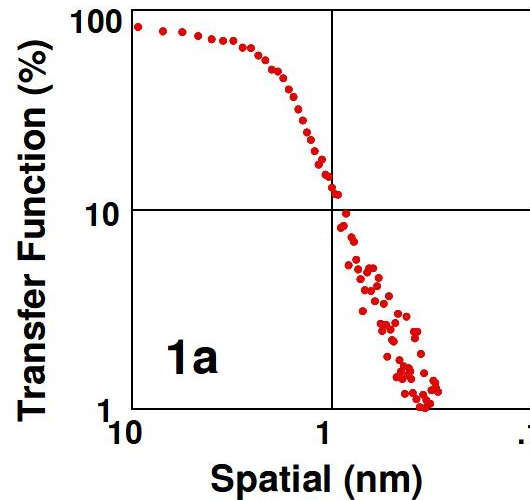
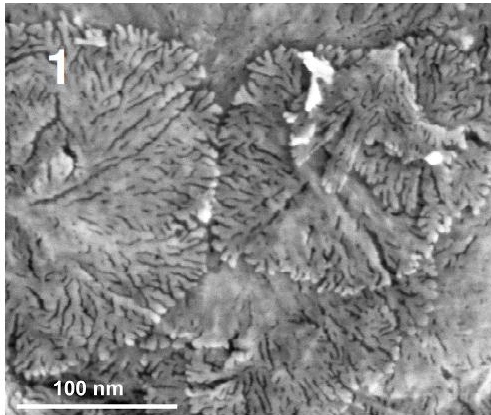


Fig 1: 'The CTF shows significant contrast is transferred below 1 nm and resolution at the point when the S/N reaches 1 is 0.7 nm'

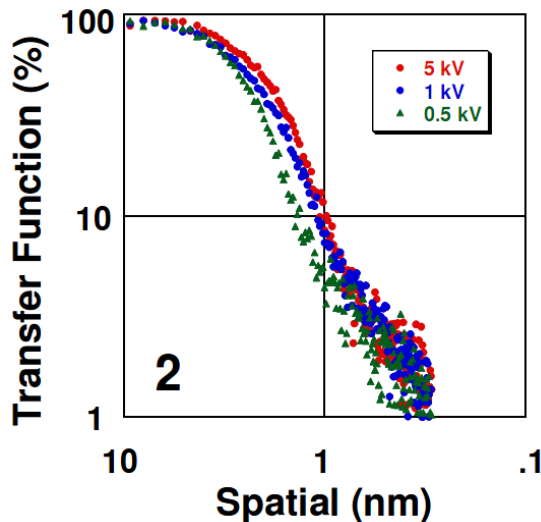


Fig 2-3: 'at 0.5 kV the useful image information limit is no worse than 1.1 nm'

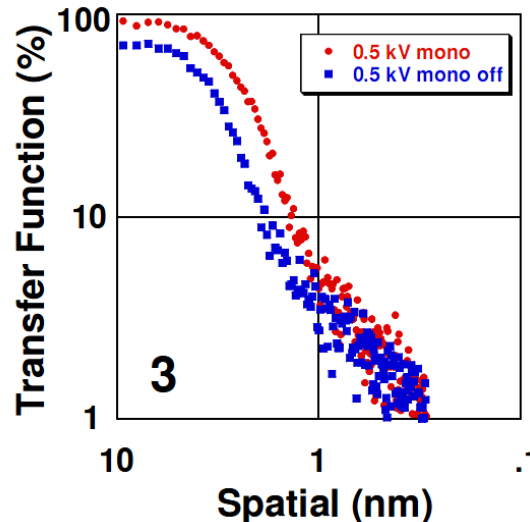


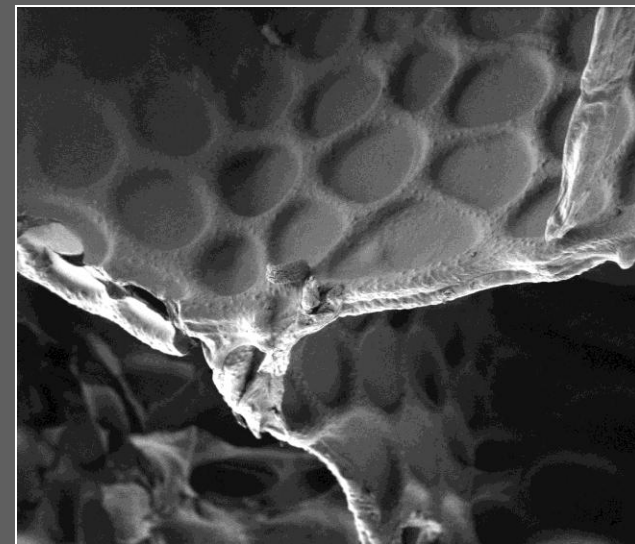
Figure 1. Pt particles imaged at 1 kV with monochromator in use. a) CTF obtained from figure 1. Figure 2. OTFs obtained at 0.5 kV, 1 kV and 5 kV with monochromator in use. Figure 3 OTFs obtained at 0.5 kV demonstrating resolution improvement with monochromator use.

More contrast (with XHR)

The 2010 detection suite for SEM and DualBeam

Why ?

- 'Higher' quality SEM and focused ion beam (FIB) images
 - Signal to noise (S/N)
- More and more precise contrast
 - Collecting all the electrons, filtering
- Low dose UHR / XHR SEM
 - Improving contrast or S/N without increasing the beam current



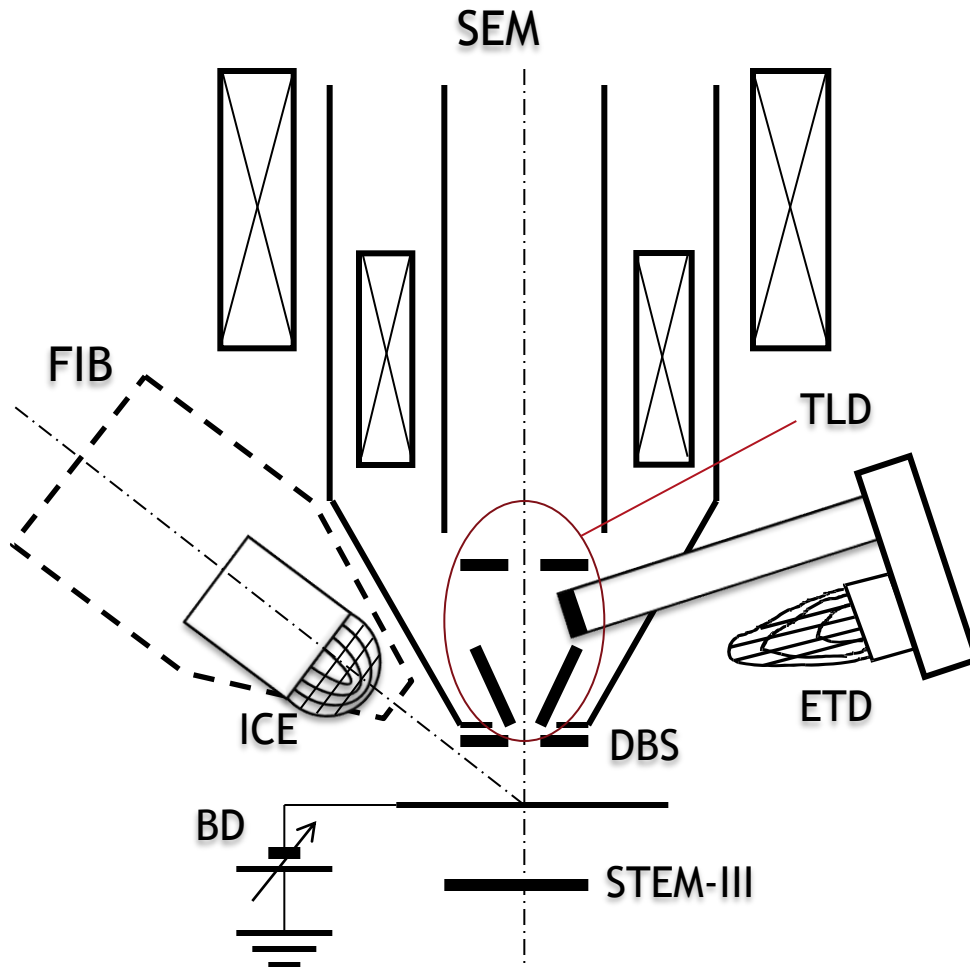
Uncoated Pollen, imaged with a beam landing energy of 50 eV

Values

- In general: more and more precise information
- Better imaging of beam sensitive samples
- High speed imaging of robust samples

More contrast (with XHR): How?

The 2010 detection suite for SEM and DualBeam



What's changed?

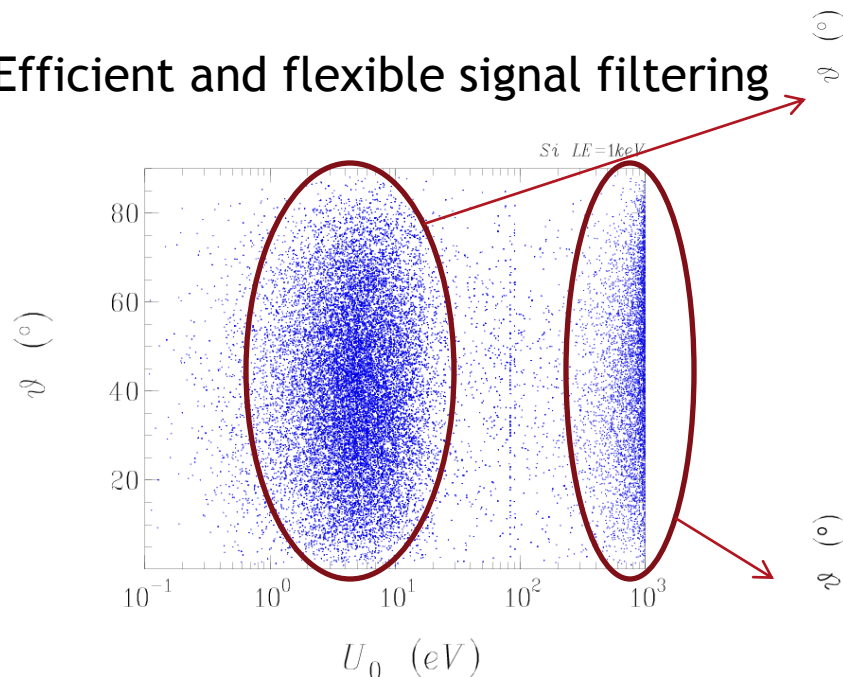
- Geometries optimization
- Solid state detection technologies
- More filtering capabilities

Acr.	Means:	Applies to:
DBS	Directional BSE detector	SE, BSE
TLD	Through the lens detector	SE, BSE
ETD	Everhart Thornley detector	SE
STEM	Transmitted electrons detector	BF, DF, HAADF
BD	Beam Deceleration	Low landing V

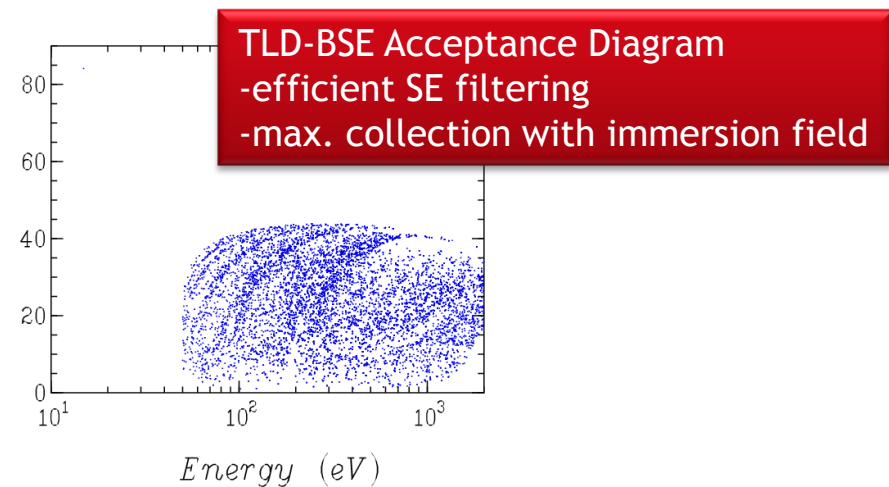
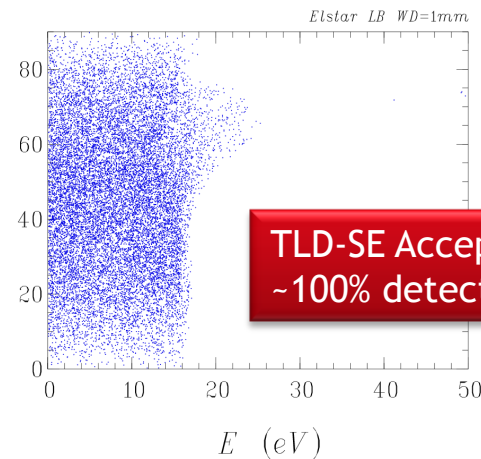
In-lens detection (TLD)

More S/N, more contrast - how do we get there?

- Optimize collection efficiency
 - Detector design
- Efficient and flexible signal filtering

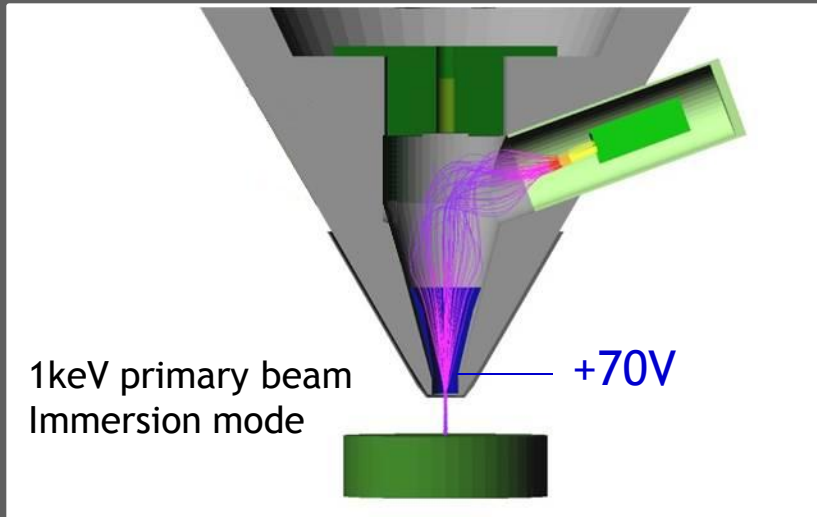


Electron spectra for 1 keV incident beam
Si sample, normal incidence
Angle u is measured from sample normal

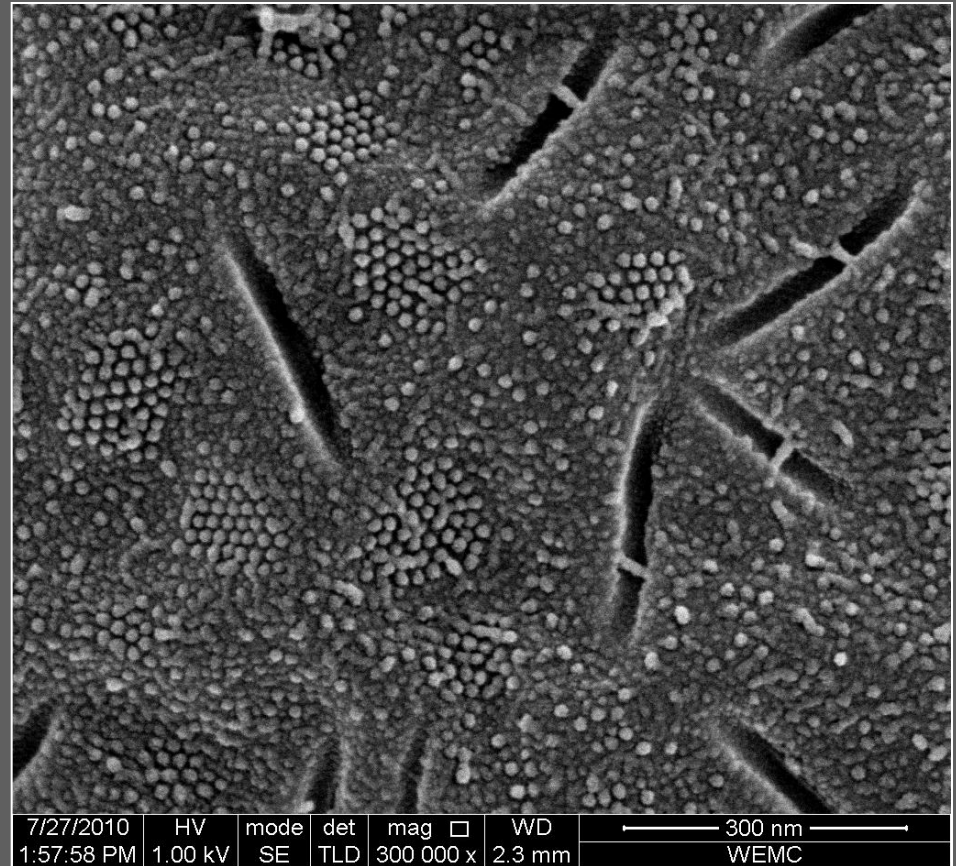


In-lens detection (TLD)

Low-dose, pure Secondary Electron detection mode



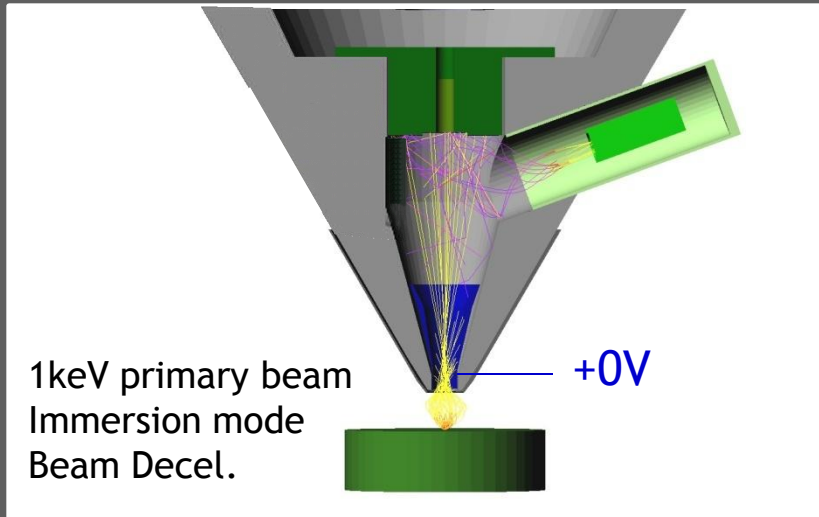
- ◆ PURE Secondary electron imaging
 - ◆ 100% of SE < 10 eV are detected
 - ◆ low dose / High speed imaging
 - ◆ Ultimate surface detail



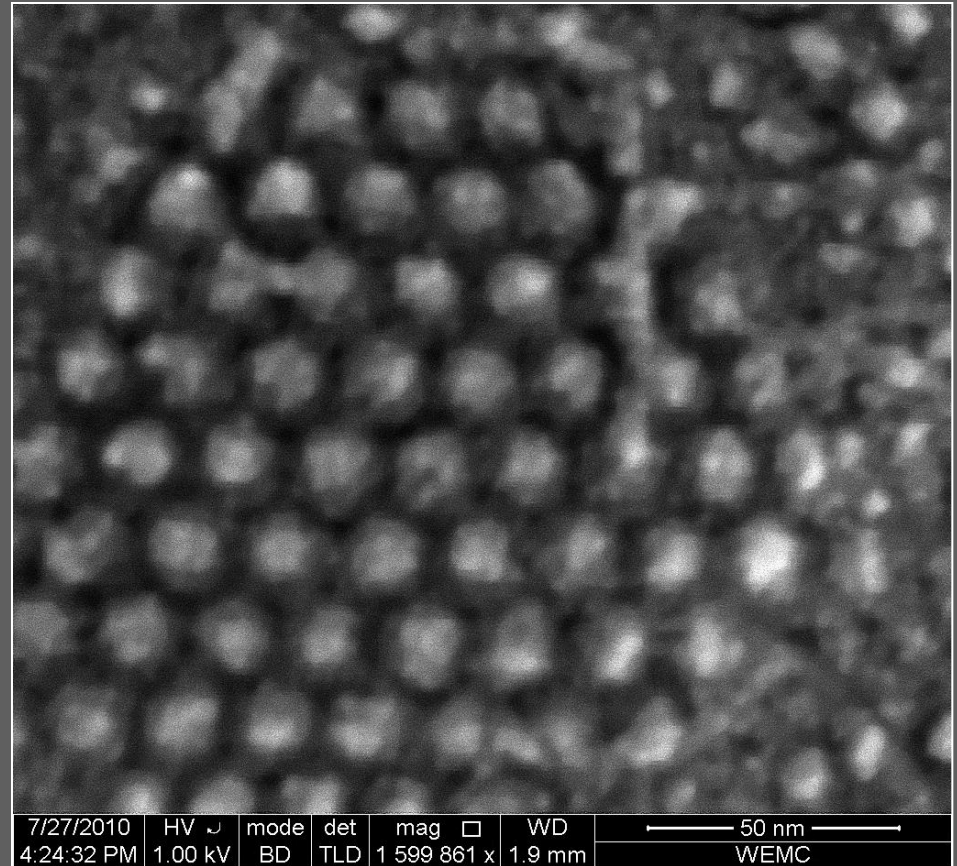
Yeast, high pressure frozen and fractured, W coated
Courtesy Adriaan van Aelst, University Wageningen
Magellan, Leica VCT100

In-lens detection (TLD)

Low-dose, High Signal mode



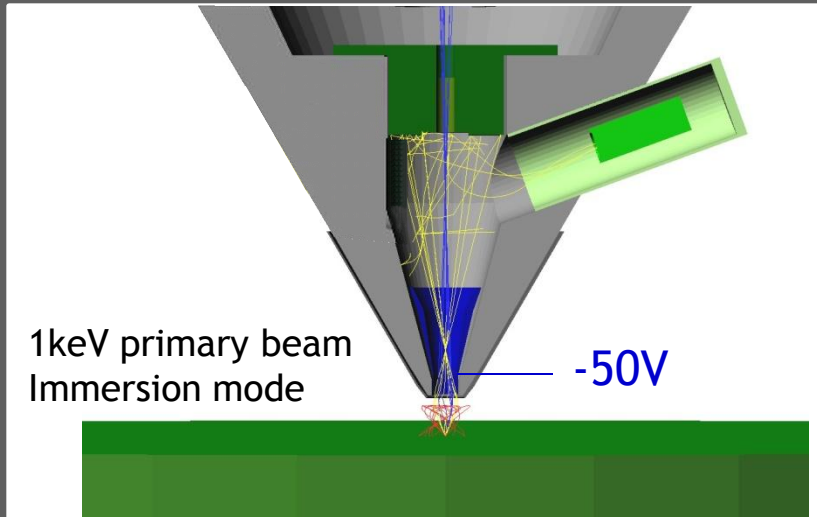
- ◆ High Signal (SE heavy) imaging
 - ◆ Lowest dose / Highest speed imaging
 - ◆ Lower beam/sample interaction
 - ◆ Ultimate surface detail



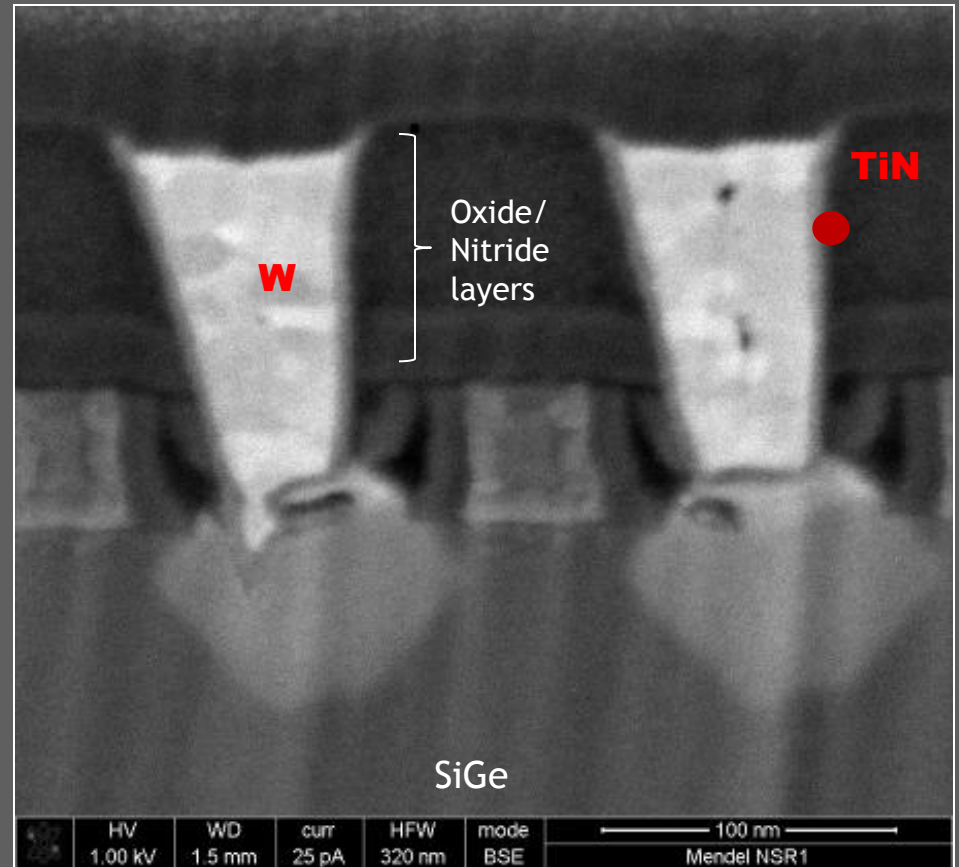
Yeast, high pressure frozen and fractured, W coated
Courtesy Adriaan van Aelst, University Wageningen
Magellan, Leica VCT100

In-lens detection (TLD)

High signal, pure BSE mode



- ◆ Pure or Mixed BSE imaging
 - ◆ low dose / High speed imaging
 - ◆ Lower beam/sample interaction



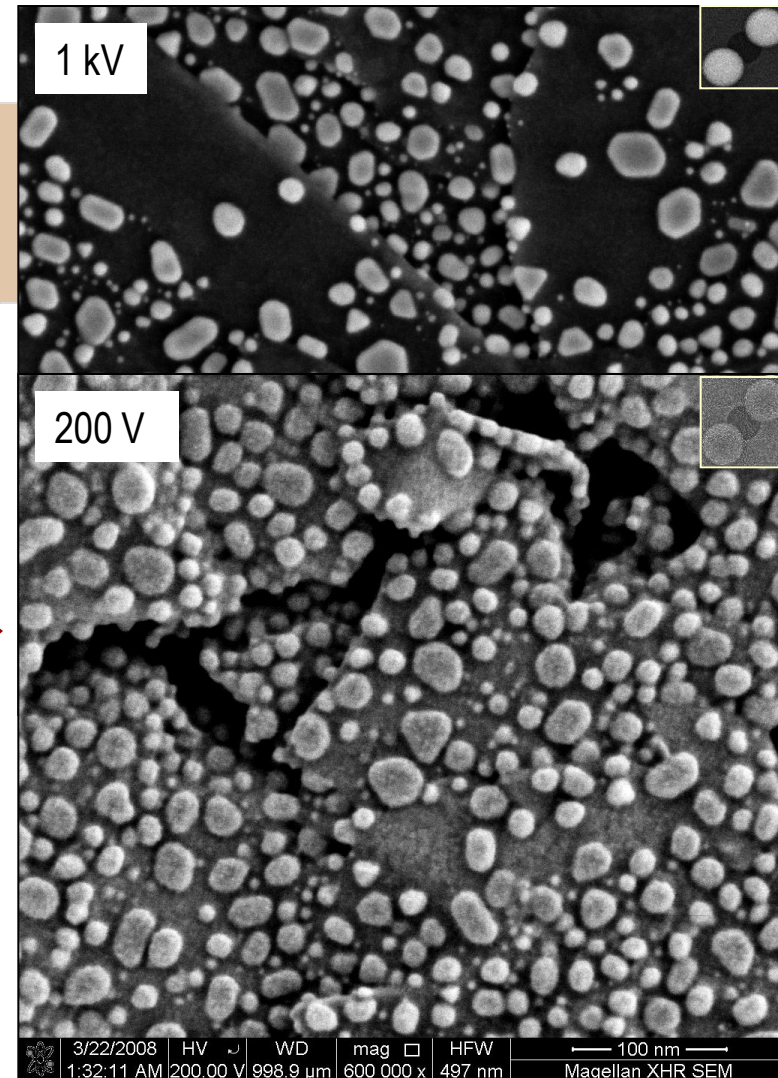
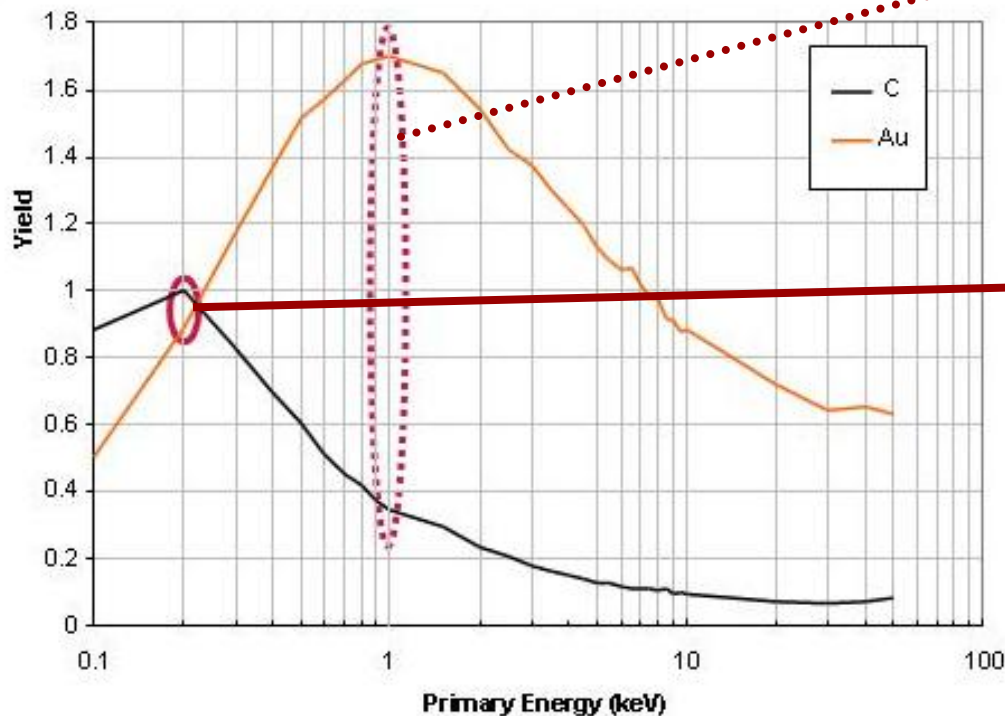
Cross section of a 45nm device
at 52deg tilt

In-lens detection (TLD)

What modelling also allows

Column-sample-detector simulations:

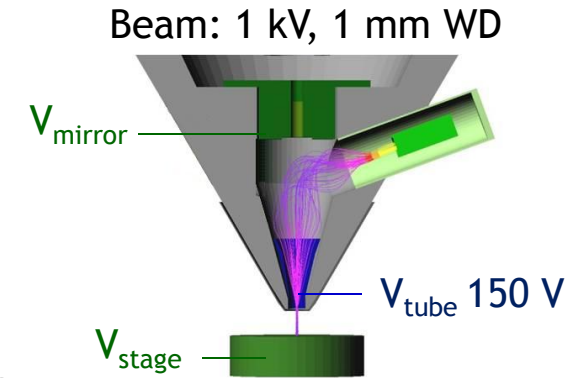
- Modeling Au and C signals at 200eV and 1keV
- Model and reality consistent



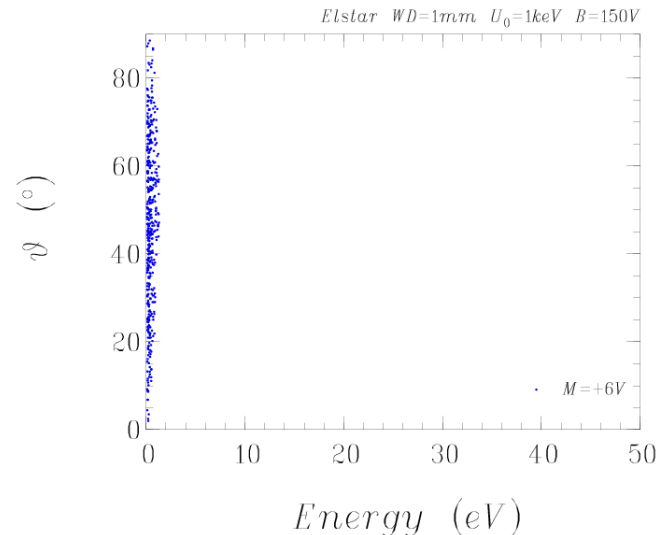
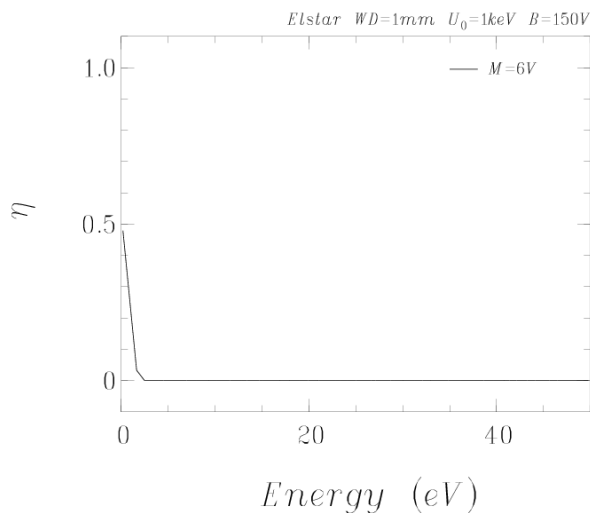
In-lens detection (TLD)

SE filtering - principle

- **High pass** SE filtering by changing sample bias
- **Low pass** SE filtering by changing mirror voltage



Example: Simulate SE collection as a function of mirror voltage (ignores SE3 creation)



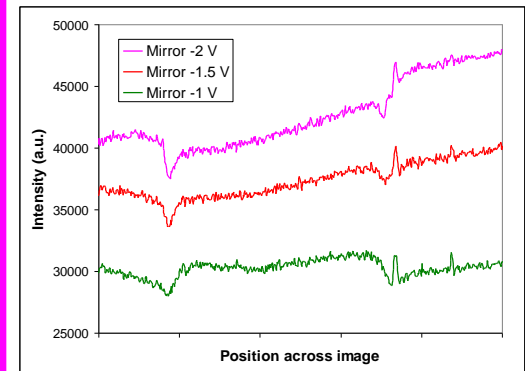
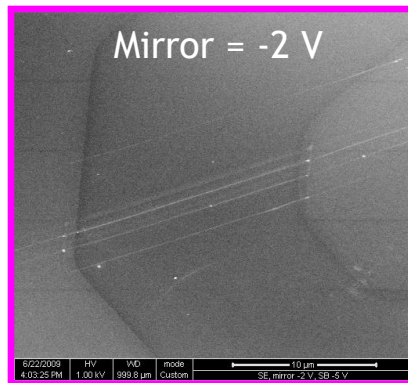
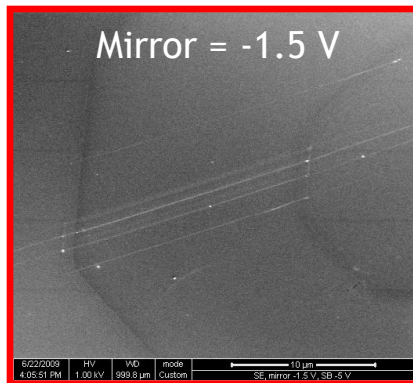
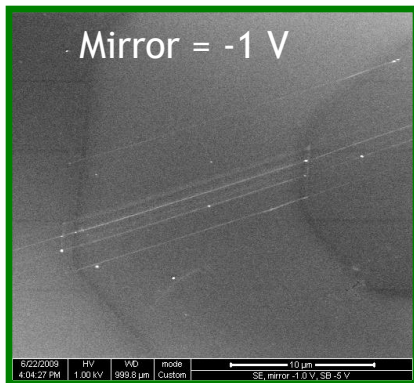
Beam: 1 kV, 1 mm WD
 $V_{\text{tube}} 150 \text{ V}$
Stage 0 V
Mirror 6 V to -20 V

From: Young et al, M&M 2009

In-lens detection (TLD)

SE filtering - applications

- Dopant contrast: Boron doping 10^{19} cm^{-3} in N type Si substrate



SEM: 1 kV, stage bias -5 V

From: Young et al, M&M 2009

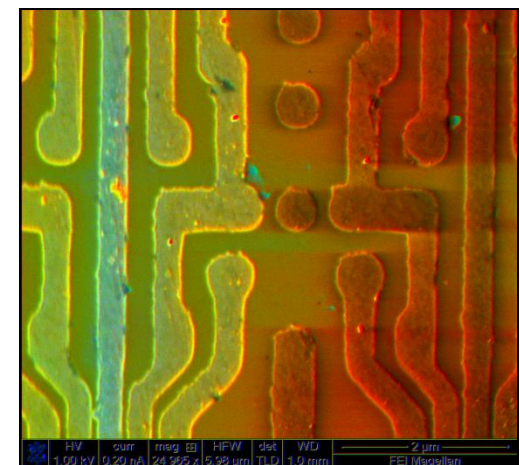
See also: Chee et al, J. Appl. Phys 108,1 (2010)

Rodenburg et al, J Phys Conf series 209 (2010)

• Other applications:

- Passive voltage contrast (e.g. In-line inspection SEMs)
- Localization of defects (due to local fields)
- Mitigate charging effects

Voltage contrast
From: Young et al, M&M 2009



Below-the-lens SE/BSE detection (vCD, DBS)

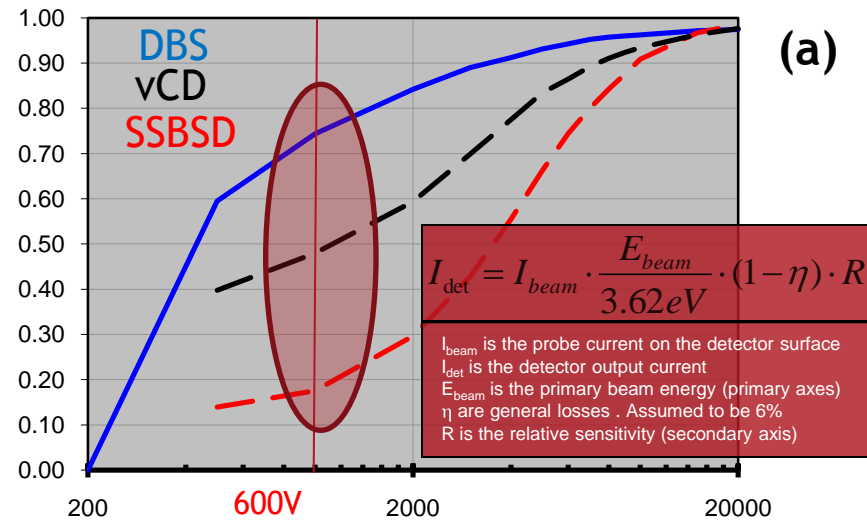
Recent technology progresses

(a) Relative sensitivity of different FEI below-the-lens solid-state detectors

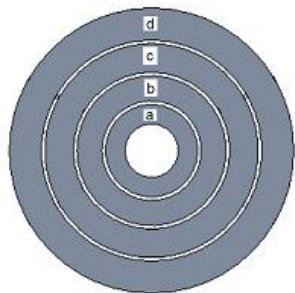
(b) Influence of Beam Deceleration

- improved large angle BSE collection
- possibility to collect SE+BSE

(c) Detector segmentation for Annular Filtering



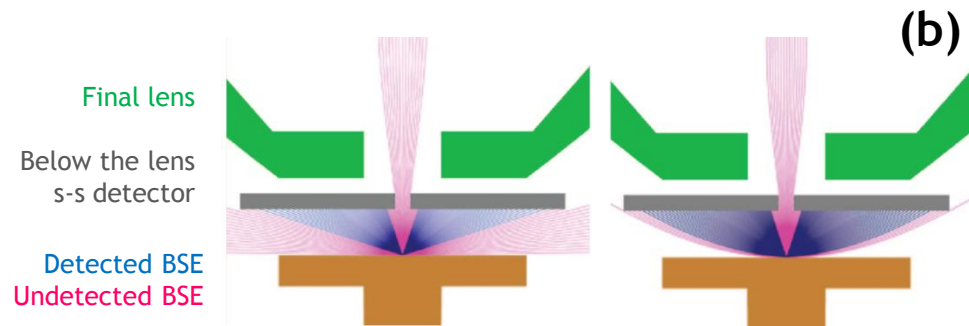
From: Gestmann et al, IMC17 proc.



The DBS detector

From: Gestmann et al, IMC17 proc.

(c)

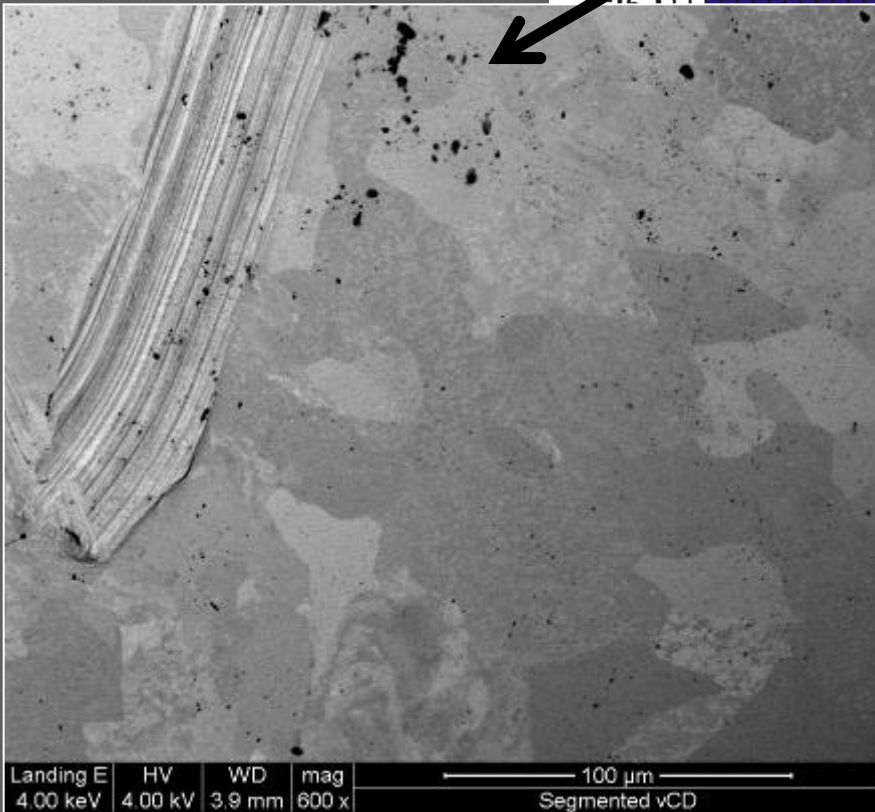
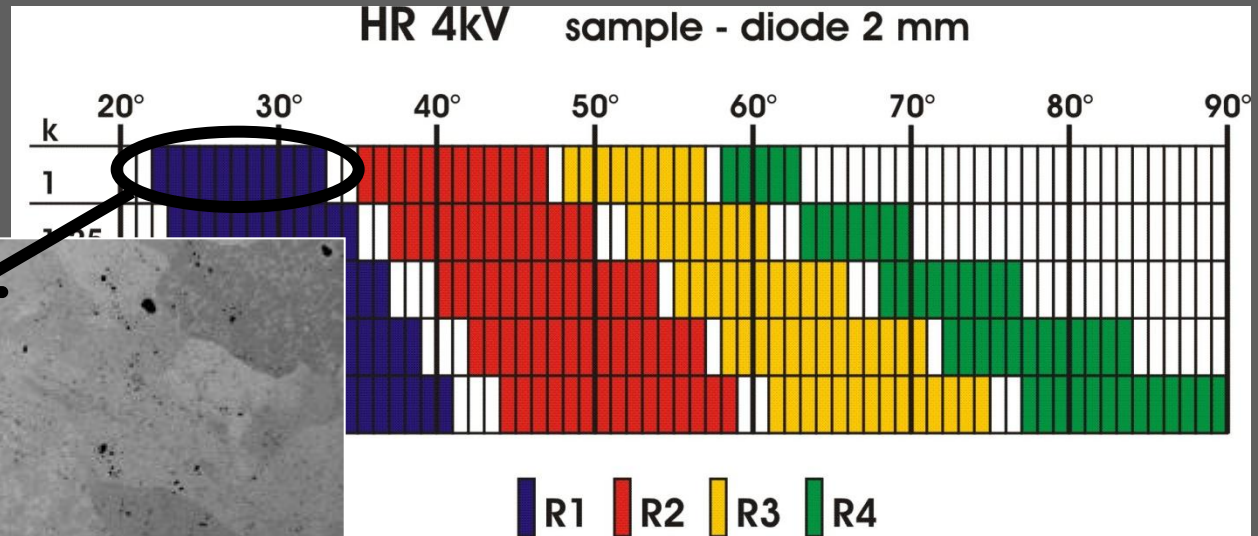


From: Phifer et al, Mic. Today, 2009

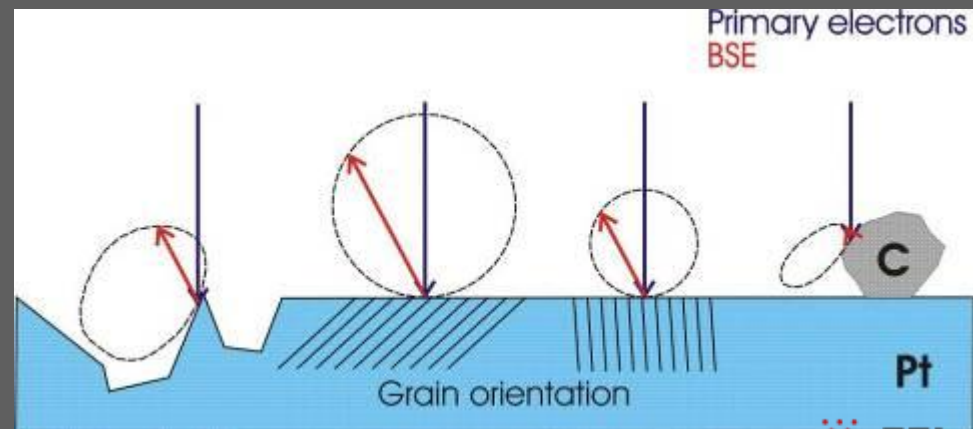
Below-the-lens SE/BSE detection

Annular segments, HR, landing energy 4 keV

k = 1

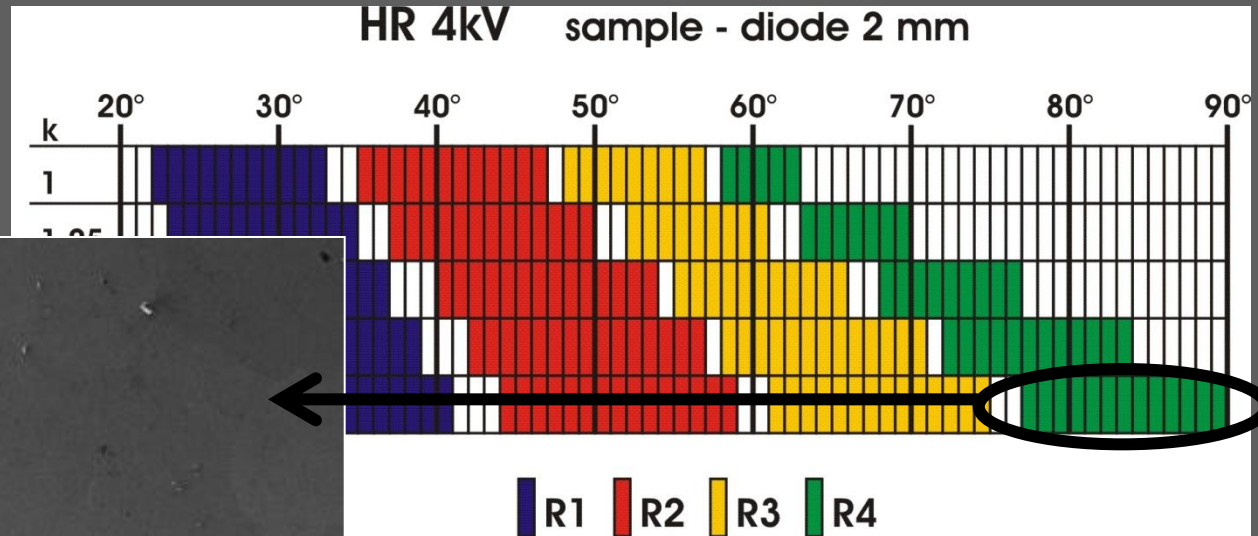


$$\bar{\theta} = 28^\circ$$

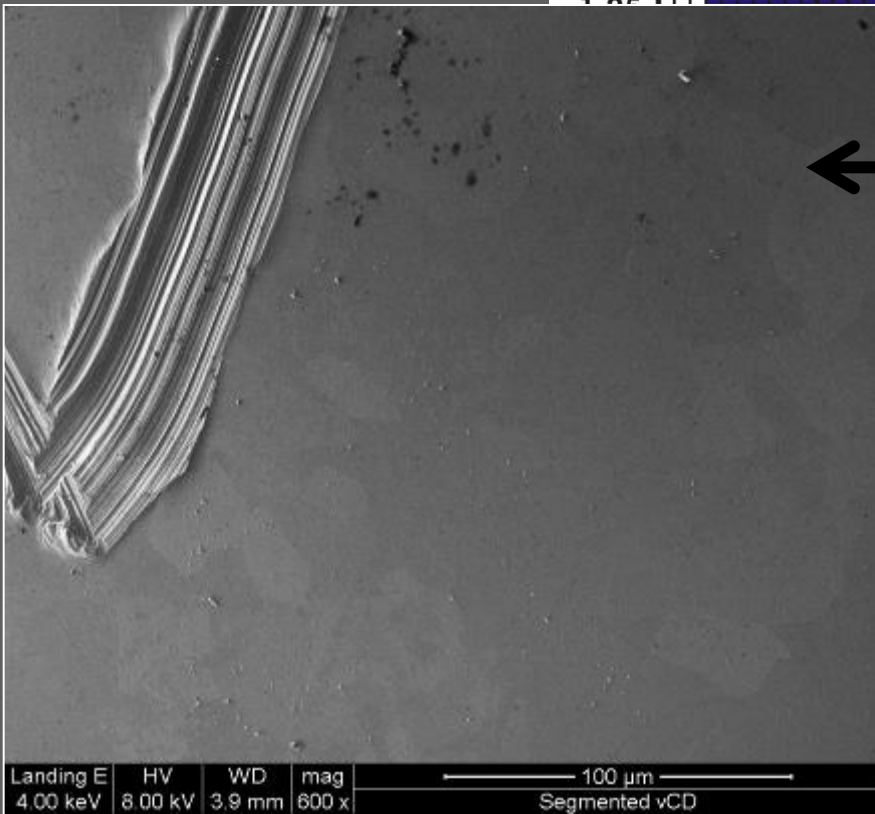


Below-the-lens SE/BSE detection

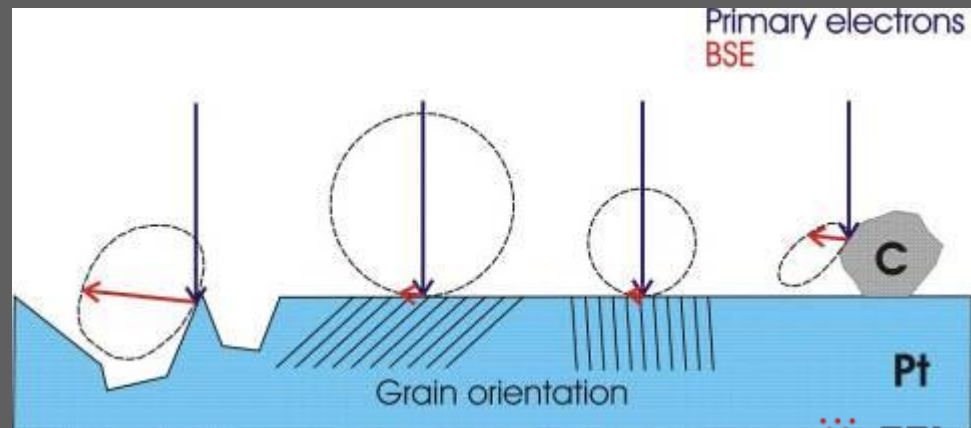
Annular segments, HR, landing energy 4 keV



k = 2

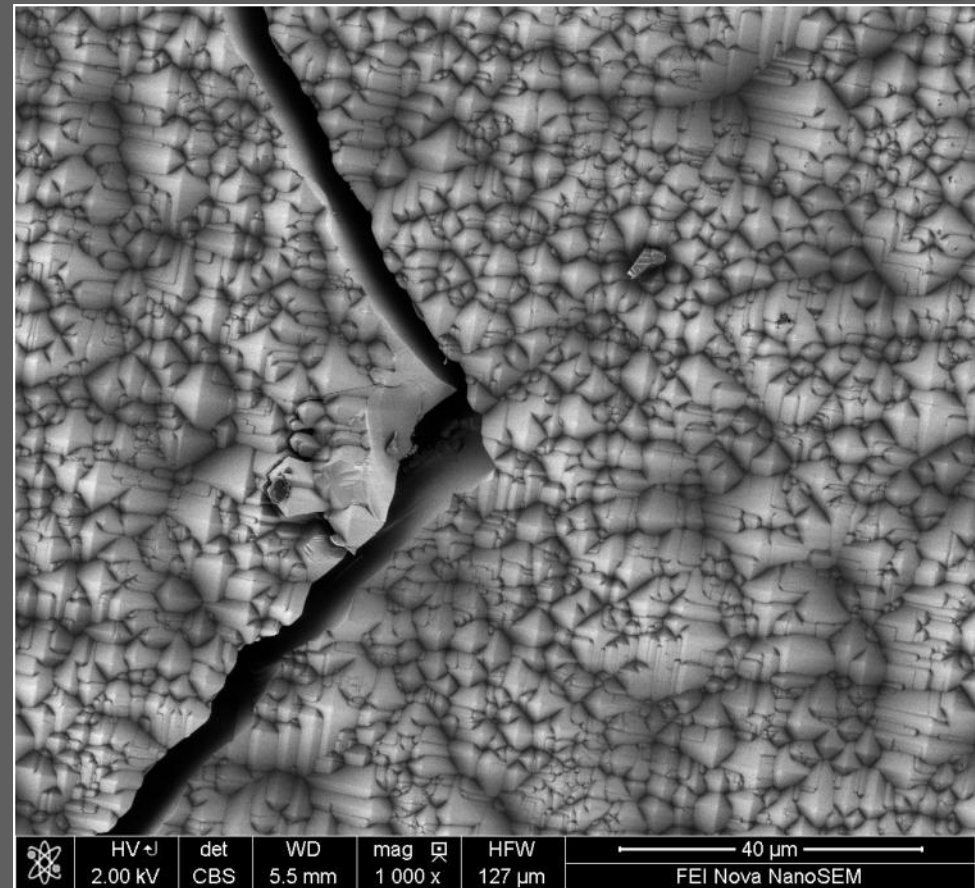
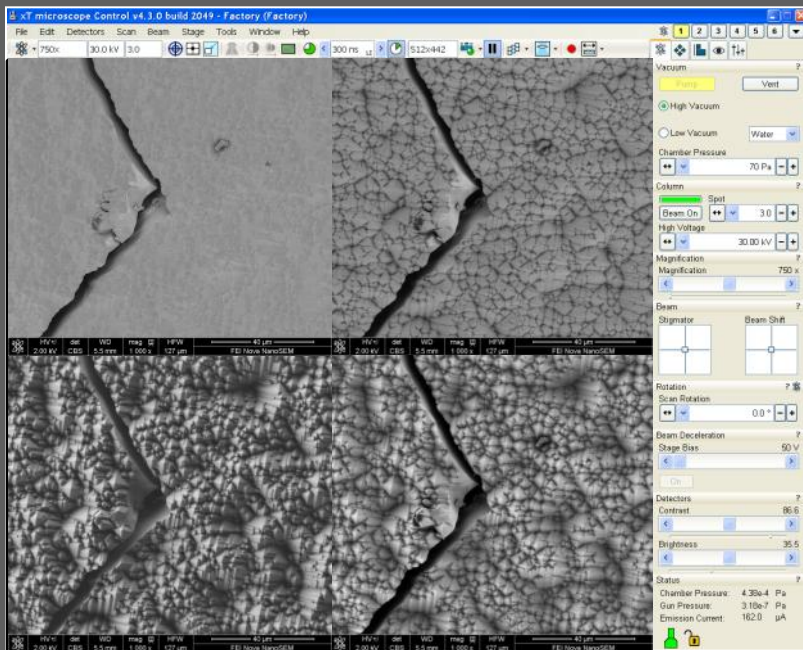
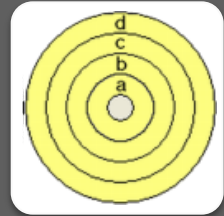


$$\bar{\theta} = 84^\circ$$



Below-the-lens SE/BSE detection

Annular filtering applications



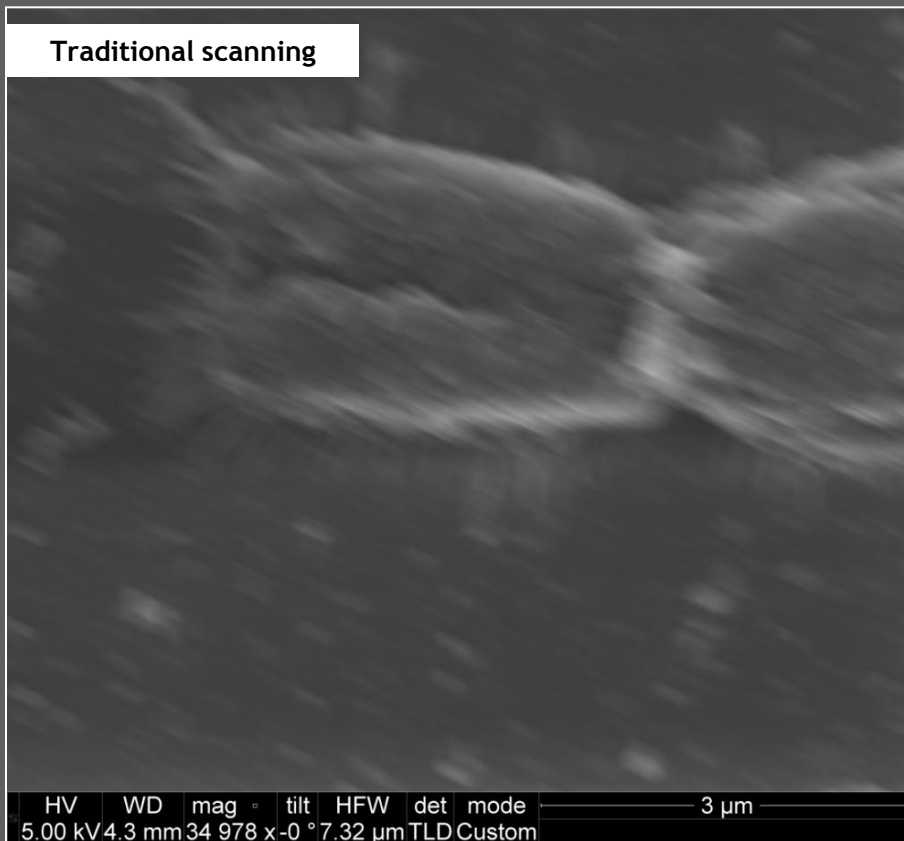
- User defined segment arithmetics
- Select only segment(s) that contain the information of interest
- Up to 4 segments (or combination of) collected simultaneously

Solar Cell Material

Other technologies to boost imaging performance

DCFI (Drift Compensated Frame Integration)

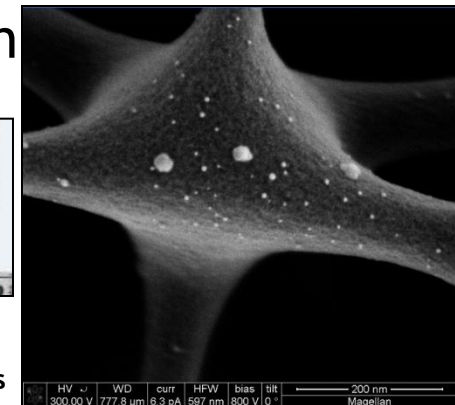
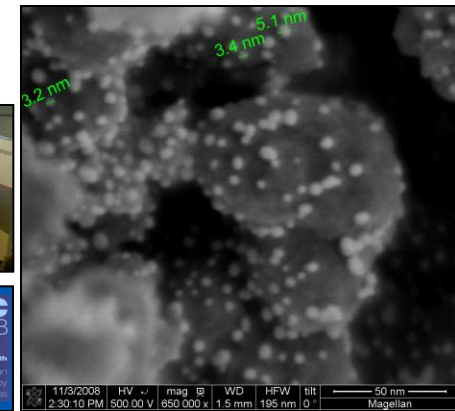
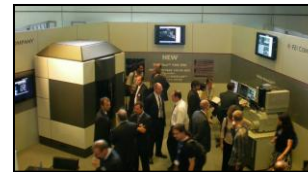
Uncoated biological sample



XHR SEM technology wouldn't work without...

Efforts made to make the instruments immune to:

- External disturbances: acoustic, vibrations, EM
 - High stability platform
 - Stage
 - Console and column
 - Optional shielding: acoustic enclosure
- ‘Internal’ disturbances: hydrocarbon contamination
 - On-the-fly trapping: cryocleaner
 - Hydrocarbon removal on chamber and/or sample surfaces: plasma cleaning



Uncoated pyrolyzed photoresist with Au nanoparticles

Courtesy of J. Michael, Microscience 2010

Conclusion

- With the recent technologies introduced on the Magellan SEM and Helios NanoLab DualBeam (column, detection and imaging), more information and higher quality images are obtained:

Technologies

- Better resolution - XHR performance
 - sub-nm resolution at high and low kV

UC, BD

- More contrast

BD, Detection

- Imaging of delicate samples

Detection, Scanning

UC = monochromator, BD = Beam Deceleration

*Extreme High Resolution & More Contrast
with Magellan SEM and Helios NanoLab DualBeam*



Thank You!

Special thanks to:

- *FEI co-workers, particularly: R. Young, S. Henstra, J. Chmelik, T. Dingle, A. Mangnus, E. Bosch, G. van Veen, I. Gestmann, D. Wall, B. van Leer*

- *McGill University, Prof. R. Gauvin*

- *Sandia National Lab, Prof. Joe Michael*

for the permission to show their results and/or use their samples.

