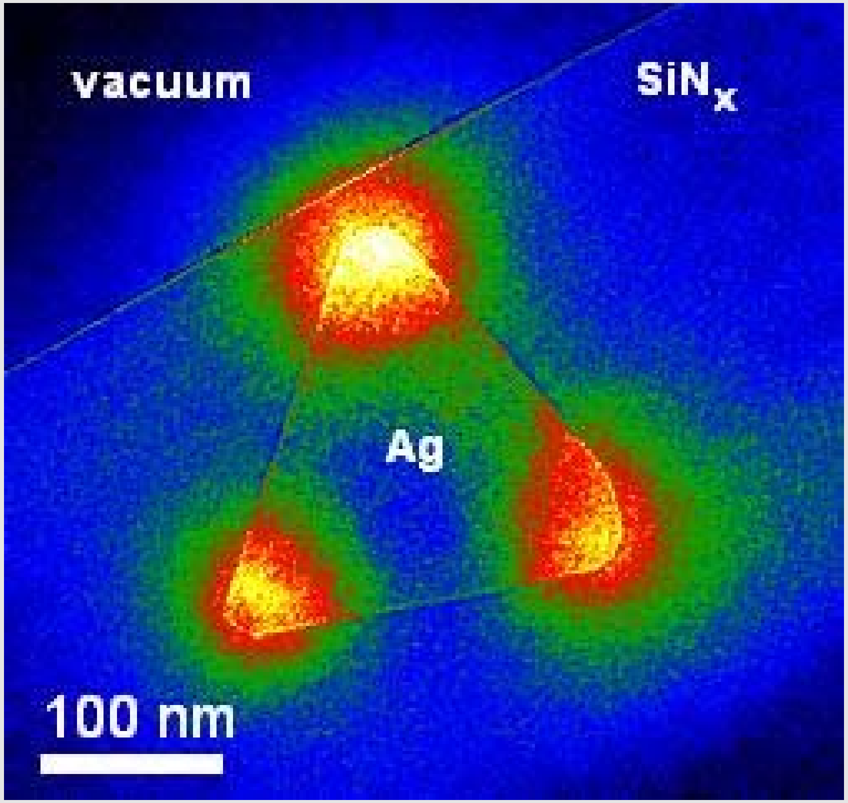
Corrected Electron Optics

Improved Resolution
and
New Analysis Capabilities



Michael Steigerwald
Carl Zeiss SMT

May 14th, 2009

Outline

- Challenges in analysis and metrology for semiconductor development and manufacturing
  - Trends in semiconductor technology along the ITRS roadmap
  - Current and future gaps in analysis and metrology
  - Opportunities for charge particle microscopy
- Corrected electron optics implementation in Transmission Electron Microscopy
  - Multipole correctors
  - Monochromators & energy filters
- Corrected electron optics implementation in Scanning Electron Microscopy
  - Mirror corrector
  - Beam separator
- Conclusion

Semiconductor technology evolution: Scaling-down

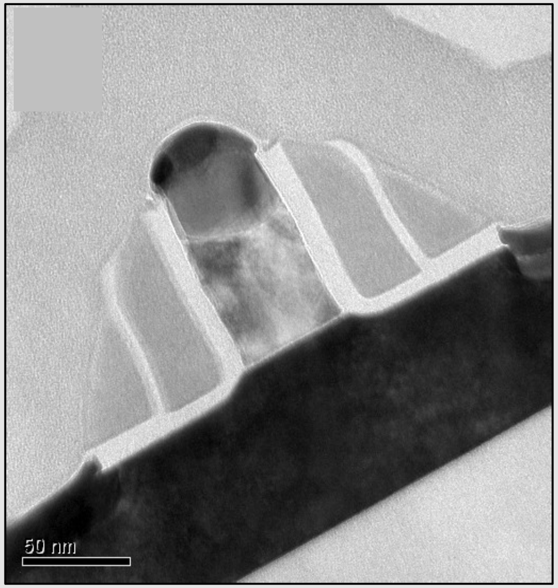
AMD’s transistor design

1998 **2004** **2008**

180nm node 130nm node 90nm node 65nm node 45nm node

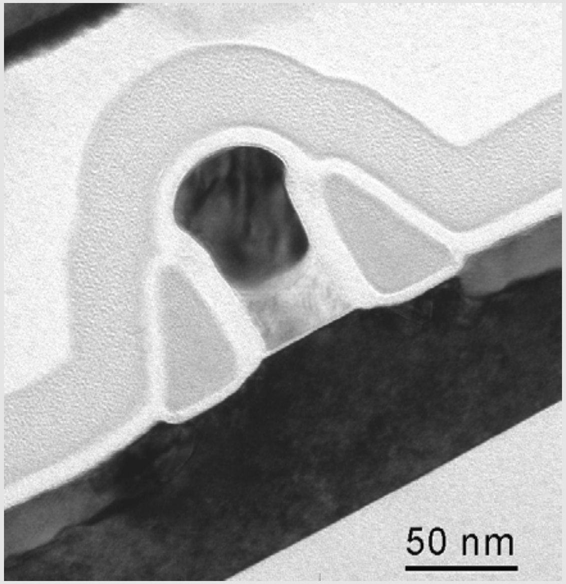
L_g = 180 nm

- Bulk Si
- Poly-Si gate
- SiO_2 gate dielectrics
- $TiSi_2$



L_g = 50 nm

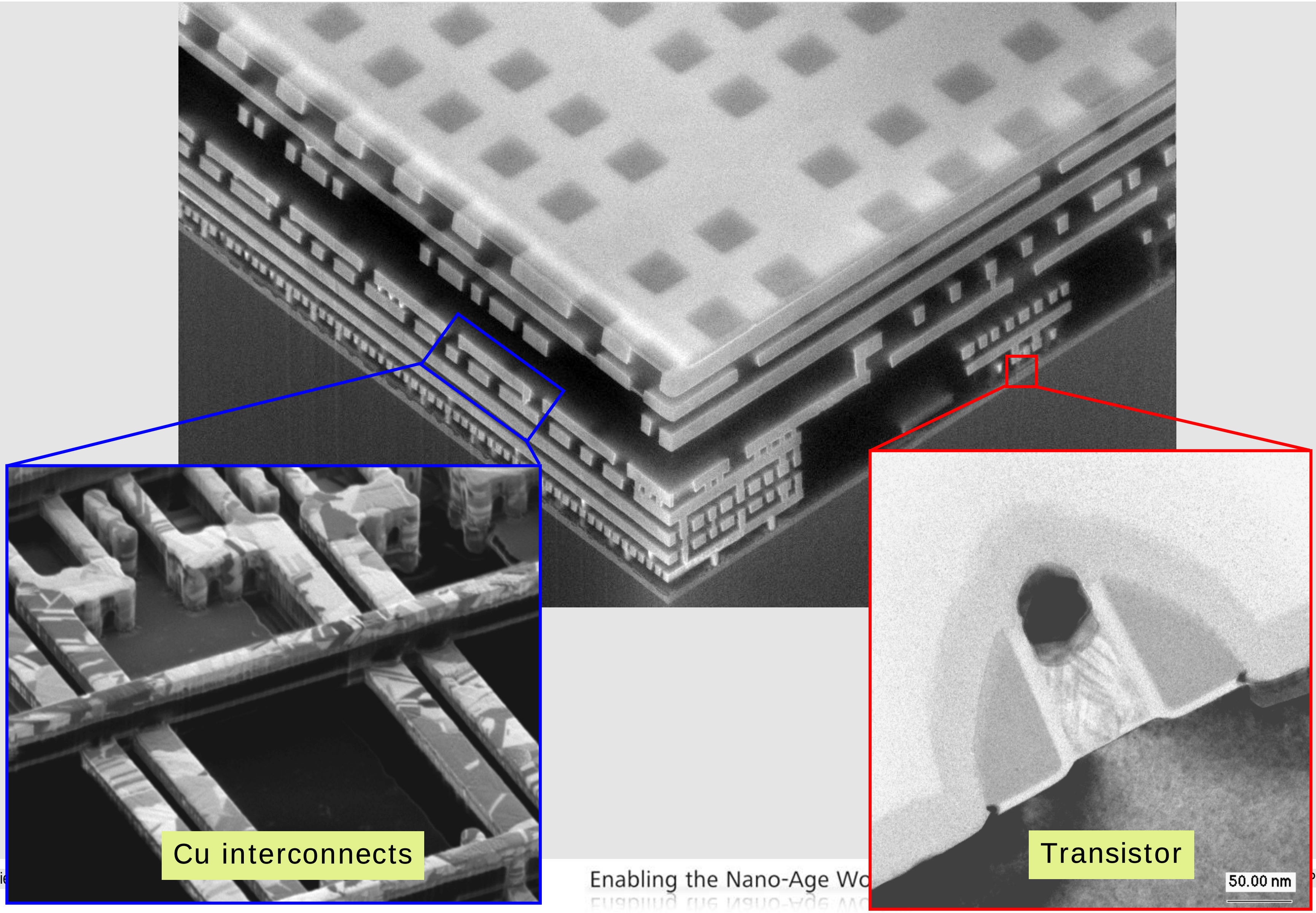
- SOI / strained Si
- Poly-Si gate
- SiON gate dielectrics
- $CoSi_2$



L_g = 45 nm

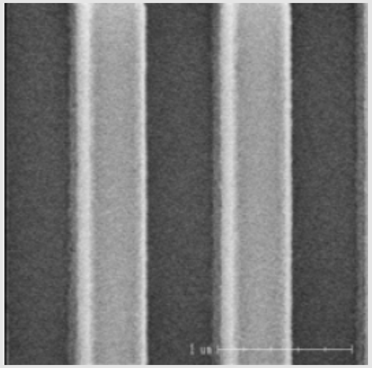
- SOI / strained Si
- Poly-Si / metal gate
- SiON/high-k gate diel.
- NiSi

Material Analysis

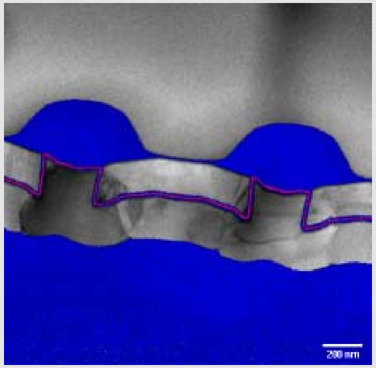


Trends in Semiconductor Technology along the ITRS roadmap

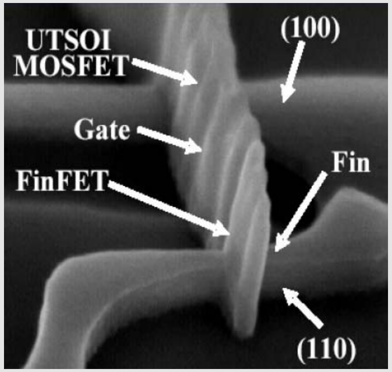
classical structures



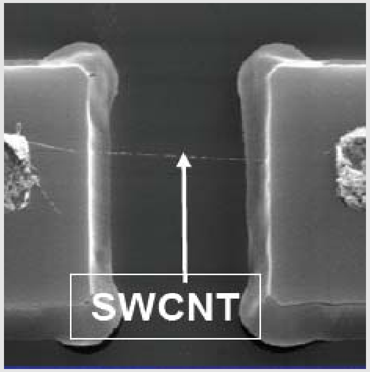
innovative materials



„non-classical“ CMOS



„beyond“ CMOS



100nm

45nm

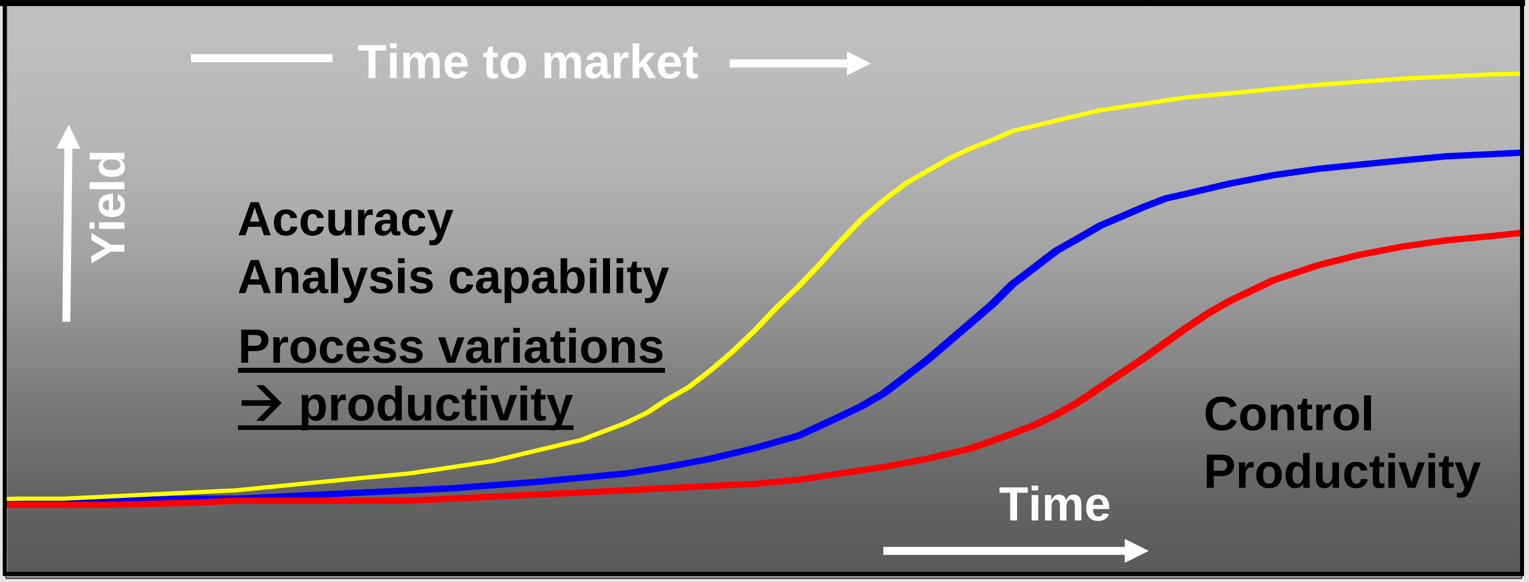
feature size	CD , film thickness , review	resolution , repeatability
new materials	properties, distribution	local analysis
3D structures	full reconstruction	resolution , reconstruction
process variations	yield, device performance	productivity, local analysis

Methods for Semiconductor analysis and characterization

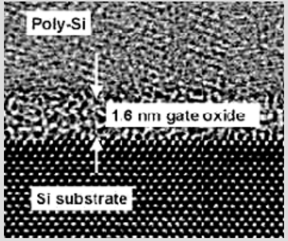
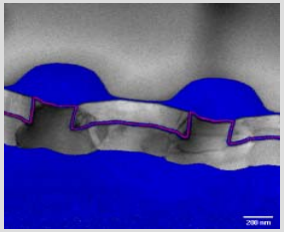
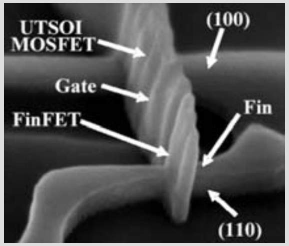
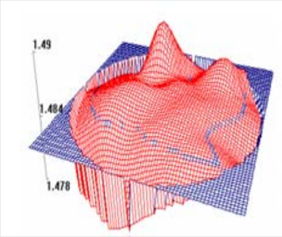
Analysis

In-line Metrology

Phase	Research	Development	Volume ramp	Volume production
Methods	TEM, SEM, SPM, Atom probe, optical, x-Ray, …	TEM, SEM, SPM, optical, x-Ray, CD, review, …	CD, optical, review, TEM/SEM, …	CD, optical, review, macro, …
Purpose	Basic learning	Process control	Process optimization	Process stability



Analytical Methods Overview

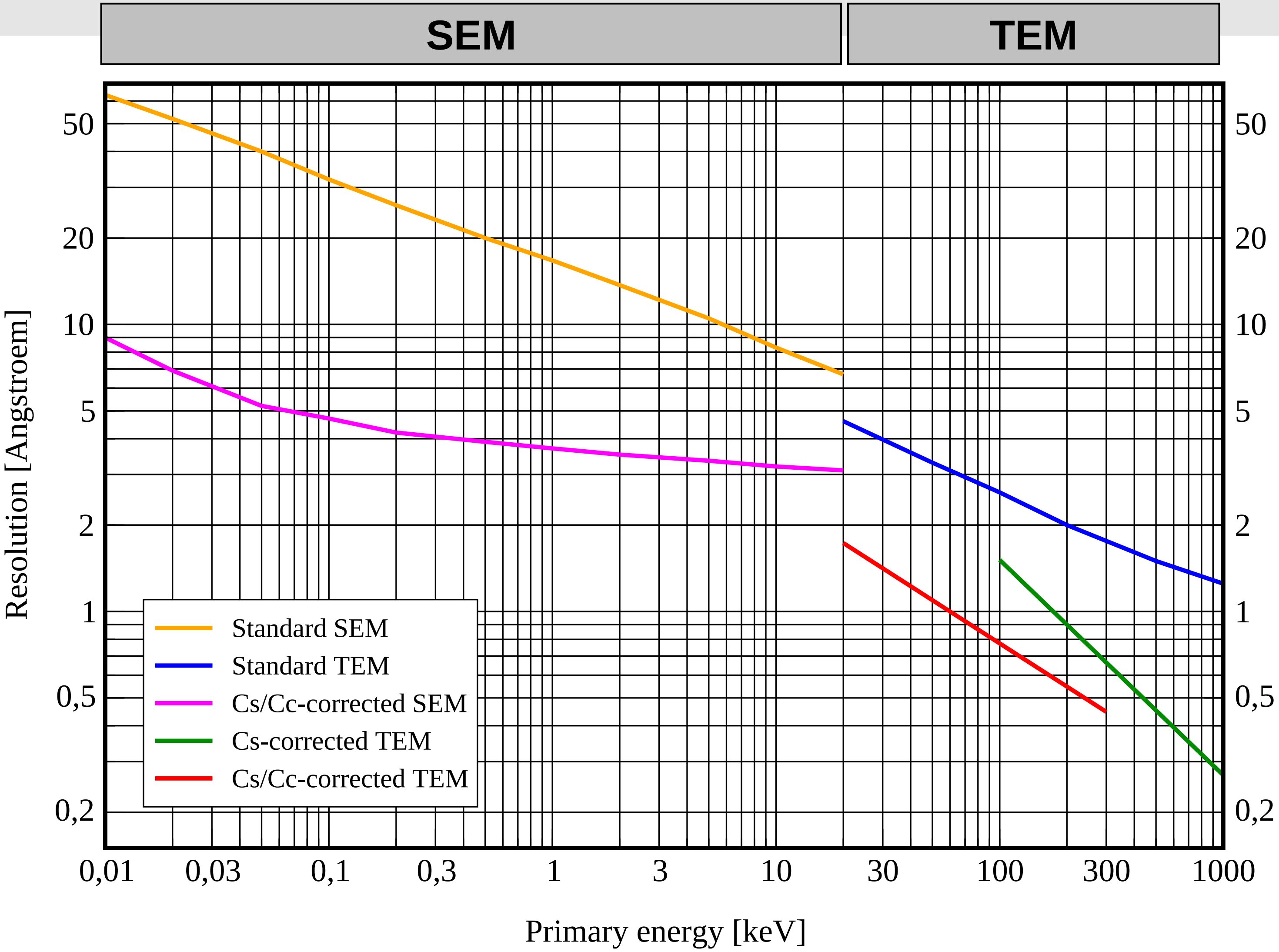
Challenge		Main methods	Major gaps
Shrink Roadmap - Resolution		▪TEM/SEM/FIB ▪He Microscopy ▪Optical methods ▪SPM	▪Preparation effort ▪Ultimate resolution ▪Resolution @ high throughput ▪Local measurement (optical)
Local Material analysis - Local Analysis		▪TEM/SEM/FIB ▪Atom probe ▪SPM ▪X-ray	▪Preparation effort ▪Local analysis capability ▪Local measurement @ high throughput
3D structures - 3D Reconstruction @ High Resolution		▪TEM/SEM/FIB ▪He Microscopy/FIB ▪Optical methods ▪Atom probe	▪Preparation effort ▪Reconstruction capability ▪Resolution @ high throughput ▪Local measurement (optical) ▪Large area 3D reconstruction
Process Variation - Productivity		▪Top down SEM/(FIB) ▪Optical methods (inspection / thickness) ▪SPM, X-ray	▪Patterned area measurements ▪Throughput ▪Local analysis capability

Major Gaps, Potential Solutions & Performance Factors in SEM/TEM

- Gap *- Potential solution*

Challenge	SEM (FIB)	TEM	Specimen	Electron optics
Resolution	Ultimate resolution *Correction at low kV*	Ultimate resolution *Correction*	Interaction volume	Energy / diffraction limit Spherical aberrations Chromatic aberrations
Local analysis	Local analysis capability *Detector schemes*	Local analysis capability *Energy filtering*	Differential cross-sections (scattering process)	Contrast transfer function Detection principles Energy resolution of detection
3D Reconstruction	Preparation effort *FIB preparation*	Preparation effort *TEM sample preparation*	Sample preparation	Surface analysis vs. transmission
Productivity	Preparation effort *FIB preparation*	Preparation effort *TEM auto preparation*	Radiation resistance (energy) Max dose	Max current Stability Ease-of-use / calibration

Resolution Range in Electron Microscopy



Diffraction

$$rd = \frac{0.61 \cdot \lambda}{\alpha}$$

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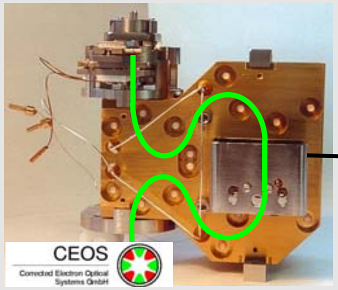
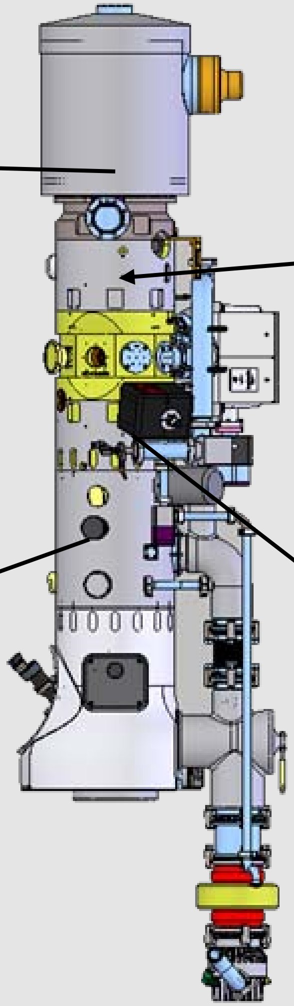
Corrected TEM Components

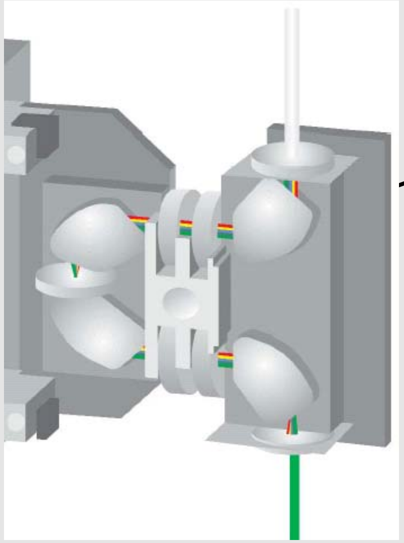
Corrected Monochromator



Illumination Corrector (STEM)



Corrected Omega Filter



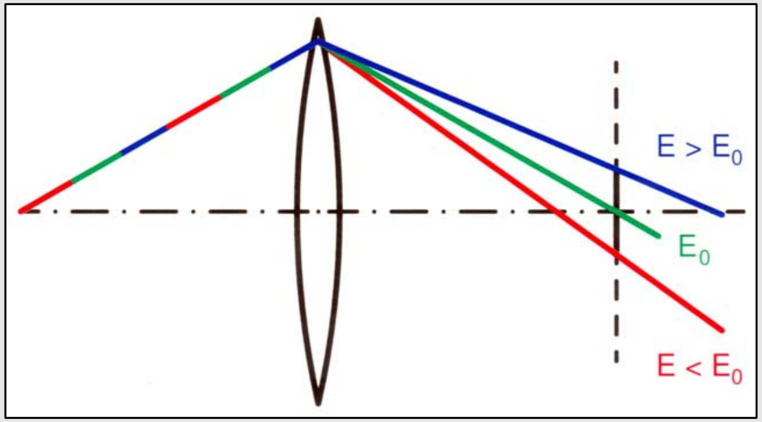
Imaging Corrector (TEM)

Aberration

a) Chromatic aberration

The slower the electrons, the shorter the focus

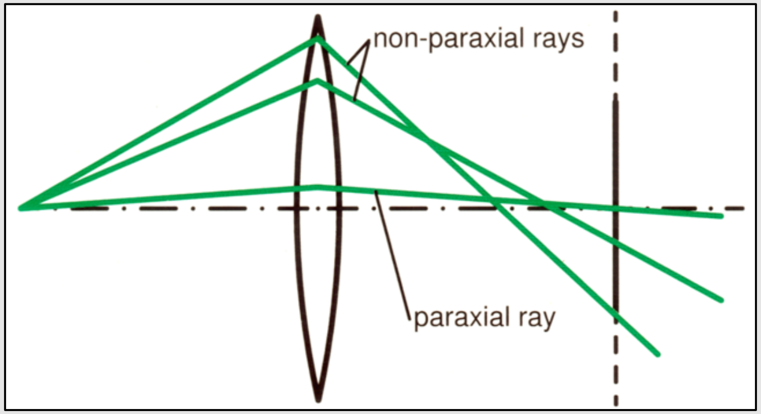
$$rc = \frac{\Delta E}{E} \cdot Cc \cdot \alpha$$



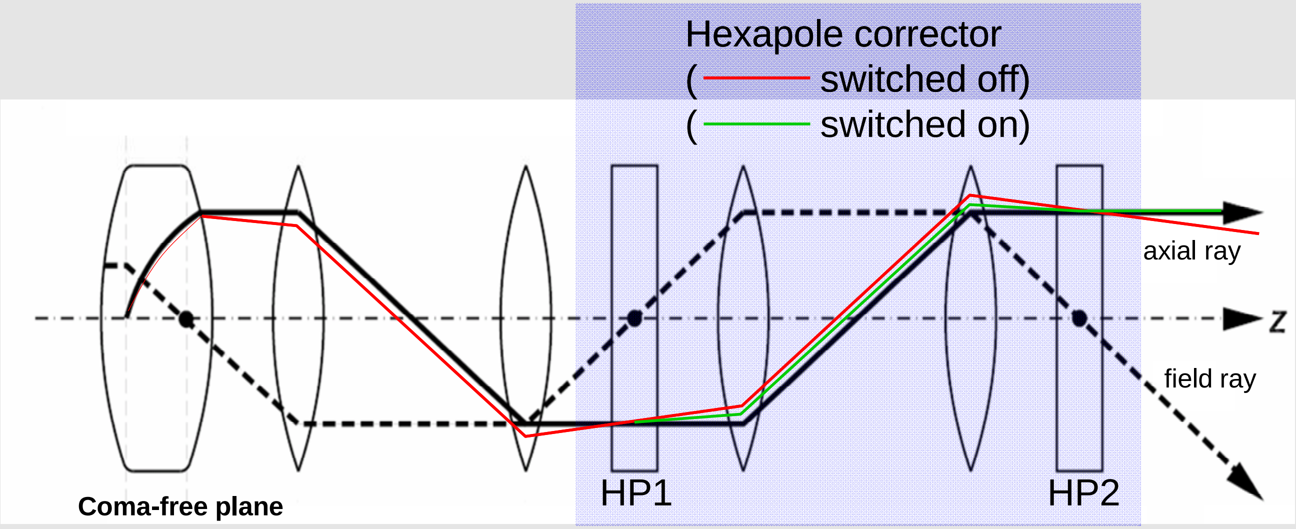
b) Spherical aberration

The higher the slope, the shorter the focus

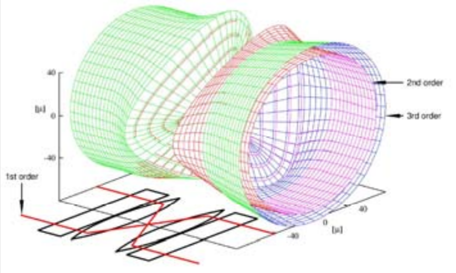
$$rs = Cs \cdot \alpha^3$$



Aberration Correctors



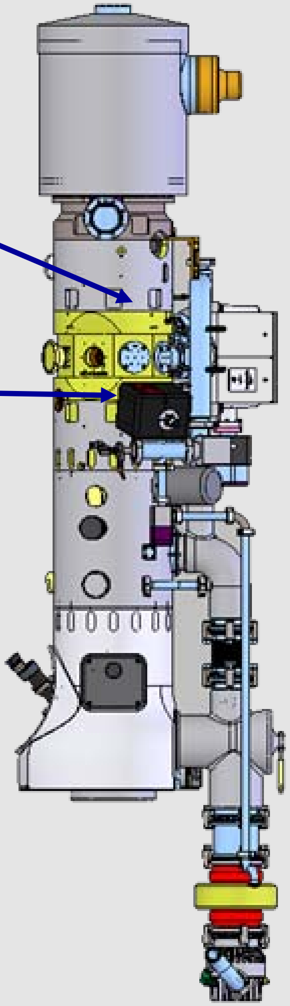
CEOS
Corrected Electron Optical Systems GmbH



Magnetic hexapole doublet	Cs	often combined with monochromator
Electric-magnetic quadrupole-octupole	Cs / Cc	Various configurations for TEM and SEM
Electrostatic Einzel-lens-quadrupole-octupole	Cs / Cc	High requirement to stability of voltage sources, low energy

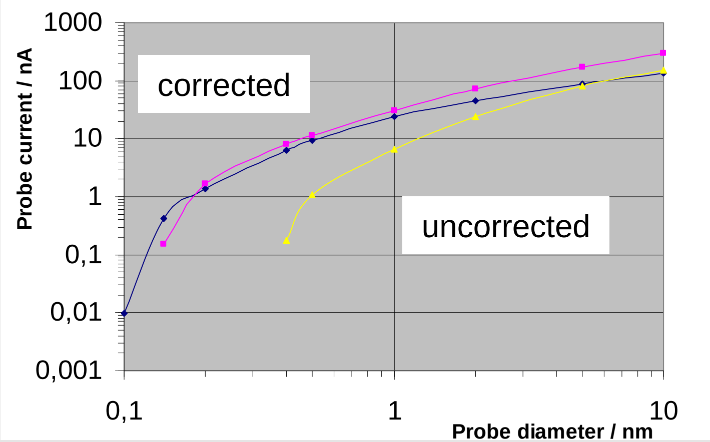
Magnetic Hexapole Doublet Corrector

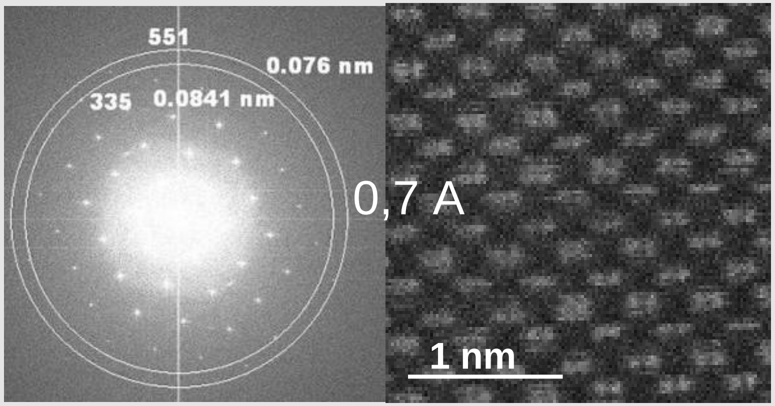
Imaging & Illumination Correctors



- **imaging**
  improved resolution down to information limit / no contrast artifacts
- **sharper and brighter electron probe:**
  higher intensity / better signal-to-noise
- **ratio in STEM images (Z contrast)**
  faster analysis / shorter acquisition

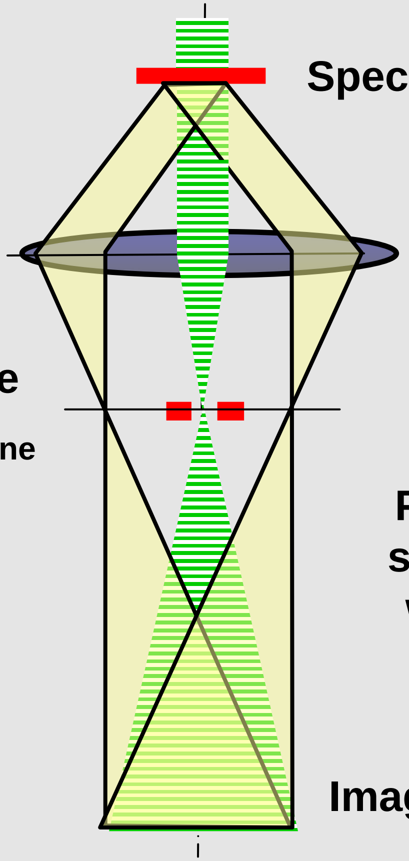
Probe current





Zoom onto Si

Magnetic Hexapole Doublet Corrector for Phase Contrast Microscopy



Specimen

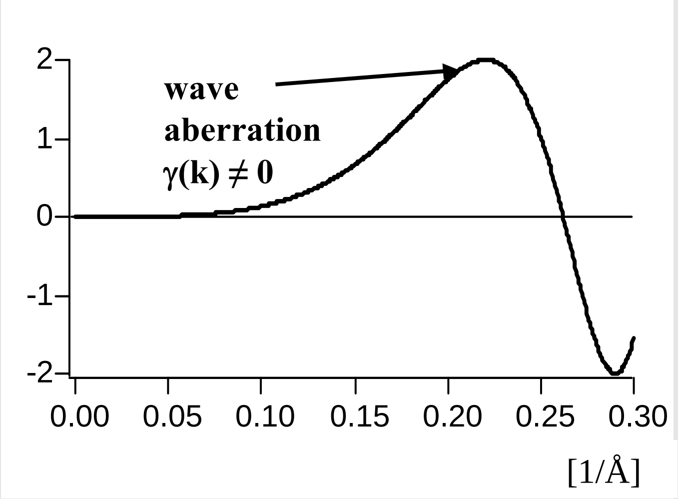
Objective lens

Phase Platte

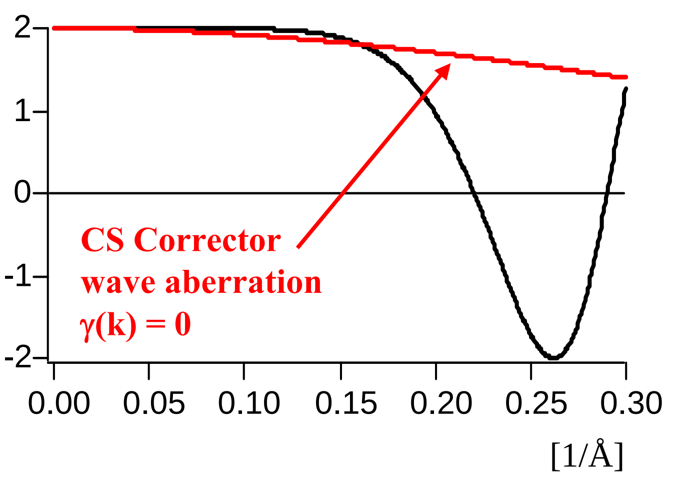
in back focal plane

Phase shifted wave

Image plane

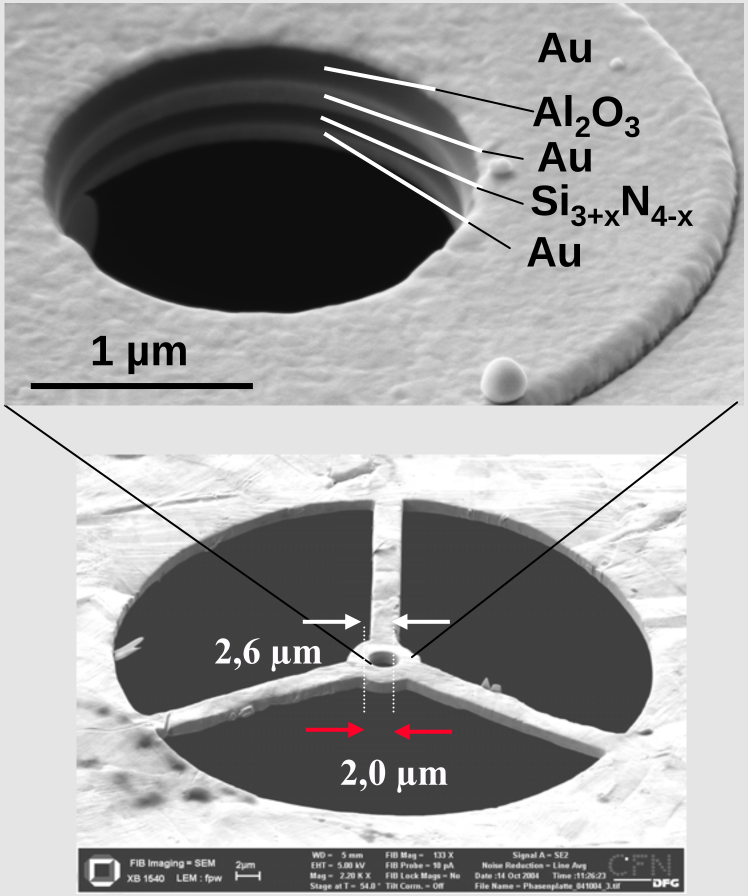


Phase shift φ(k) = 90°

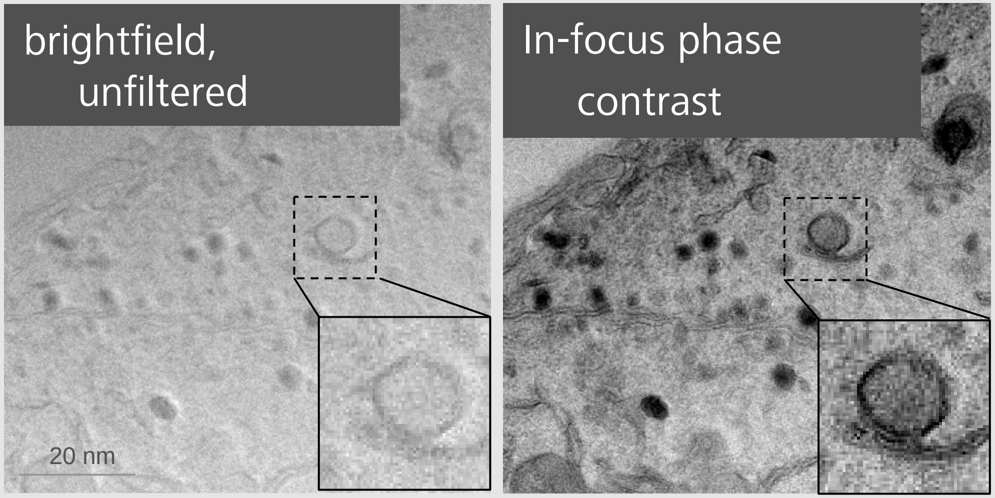


$$CTF:\ 2\sin\left(\frac{\pi}{2}\underbrace{\left(C_s\lambda^3k^4-2\Delta z\lambda k^2\right)}_{\gamma(k)}+\varphi(k)\right)$$

Phase Contrast Realization
Boersch Phase Plate



Self-supporting electrostatic micro lens fabricated with Cross Beam by Prof. Gerthsen Uni Karlsruhe

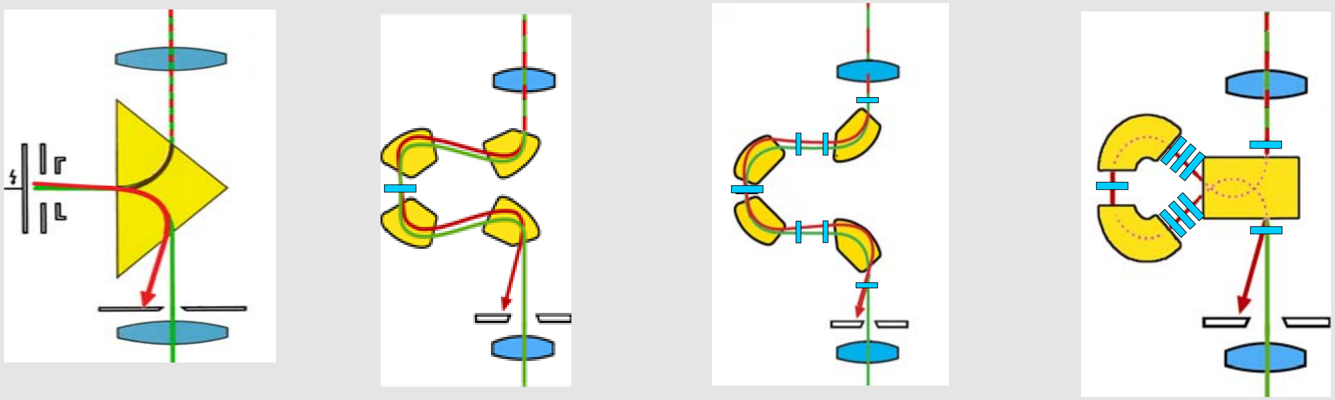


In-focus phase contrast of 200nm thick sections of plastic embedded cells. The images illustrates the improved contrast when a phase plate is used.

Potential application in semiconductor analysis: porous materials e.g. low-k dielectrics

Development of In-column Energy Filters

Progress through Innovation

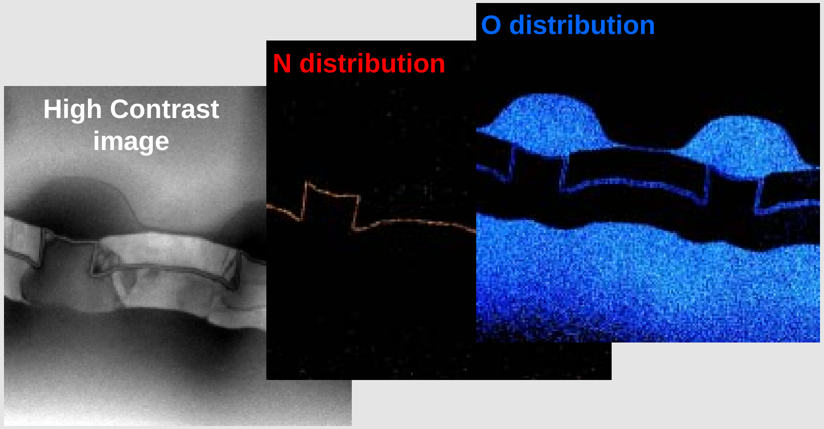


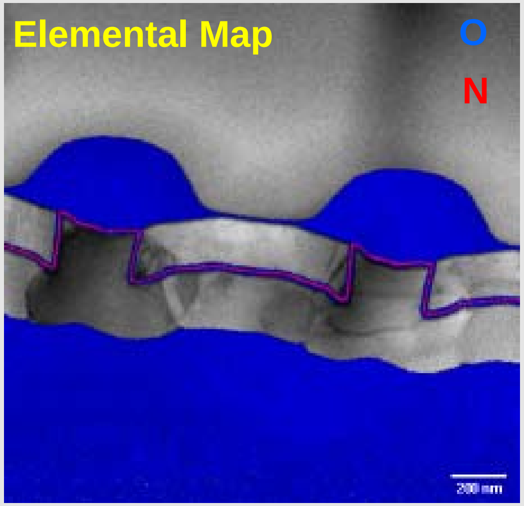
Filter Type	Prism filter	OMEGA filter	Corrected OMEGA	Mandoline filter
Instruments	EM 902	LEO 912 / 922	**LIBRA® 200FE**	SESAM
High tension	80 kV	200 kV	**200 kV**	200 kV
Dispersion	1.5 µm/eV	0.75 µm/eV	**1.85 µm/eV**	6.2 µm/eV
Error Correction	none	2nd order optimized	**2nd order corrected** **3rd order optimized**	2nd order corrected 3rd order corrected
Non-Isochromacy (energy shift across negative)	23 eV	15 eV	**isochromatic**	isochromatic
Transmissivity („acceptance“)	12 nm^2 1 eV, 80 kV	9 nm^2 1 eV, 200 kV	**190 nm^2,** **1 eV, 200 kV**	10,000 nm^2 1 eV, 200 kV

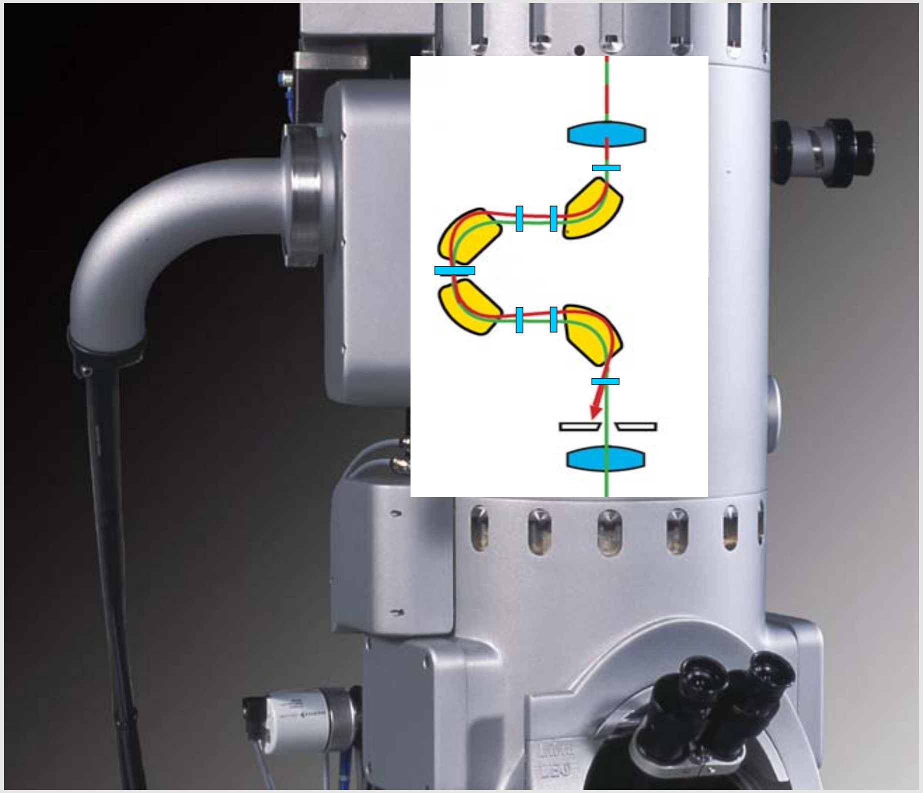
Energy-filtering TEM with Corrected Omega Filter

EFTEM of DRAM Structure

7 nm N in SiO_2 oxide layer





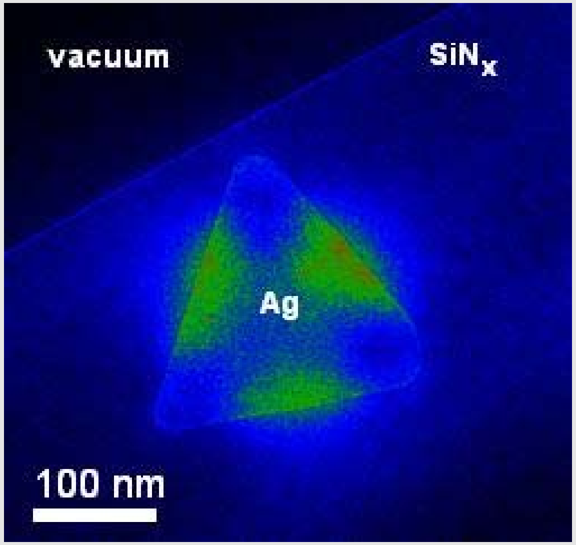


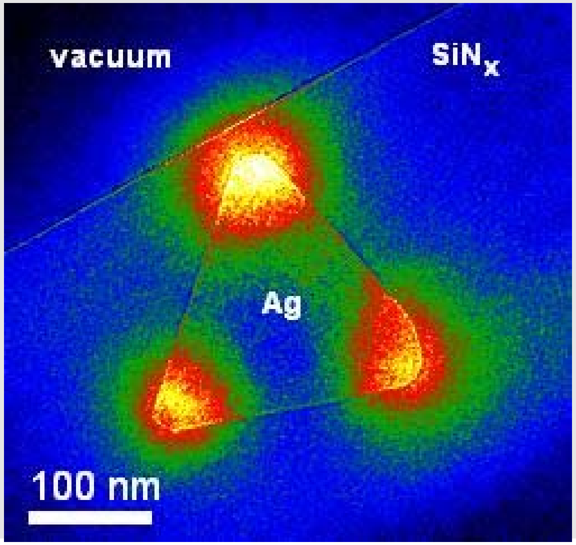
200 kV

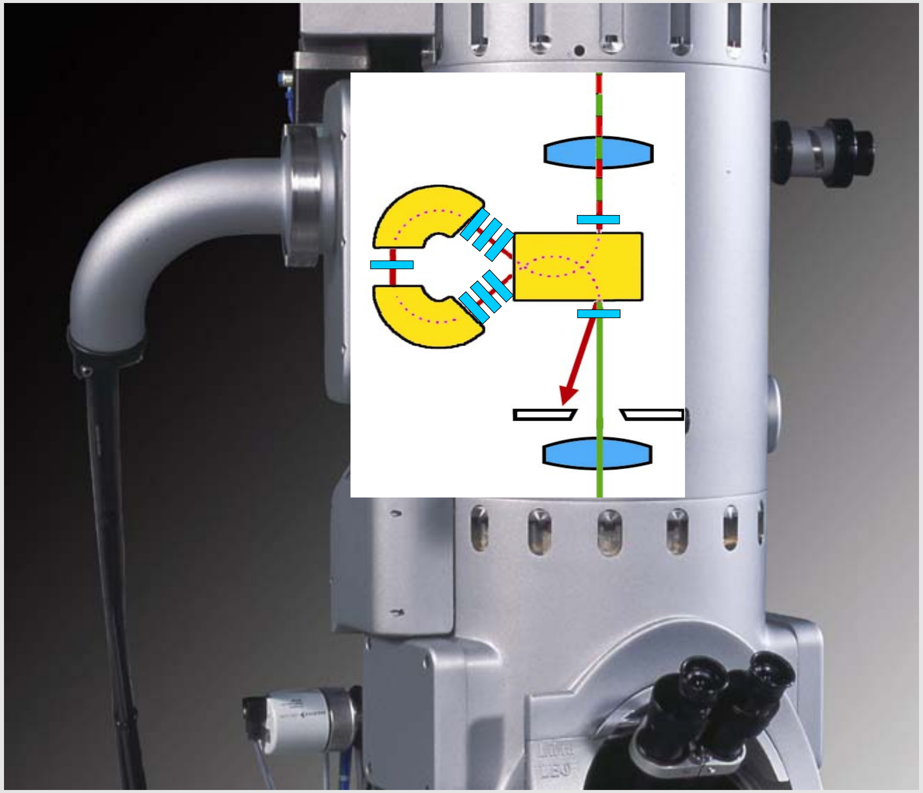
1.85 µm/eV

2nd order corrected
3rd order optimized

Energy-filtering TEM with Mandoline Filter







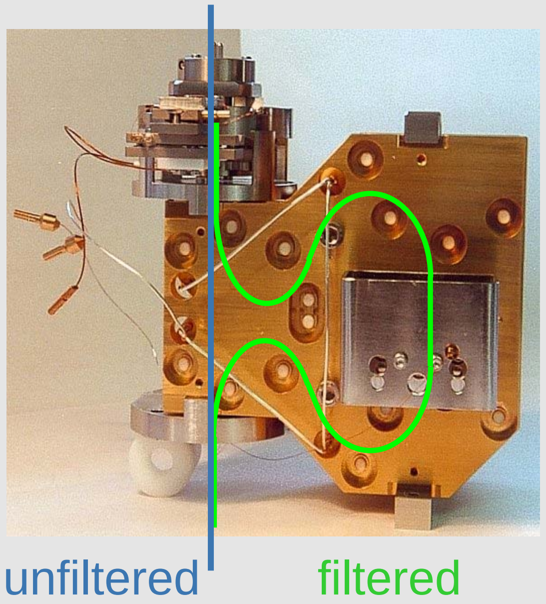
Direct energy-filtered imaging of local maxima of two vibration modes of surface plasmons in a silver nano-triangle positioned on a thin silicon nitride film.

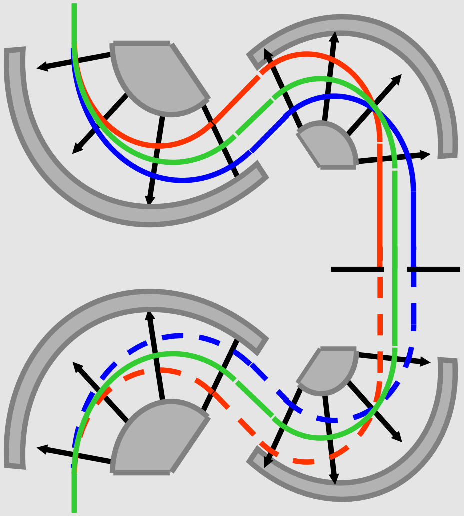
200 kV

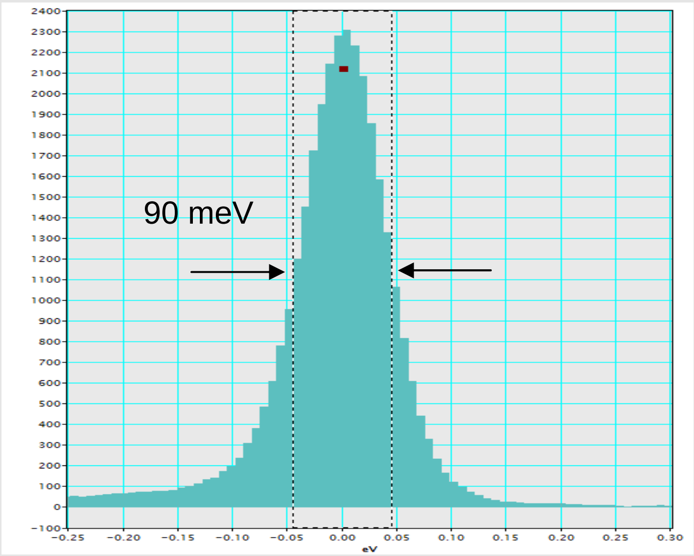
6.2 µm/eV

2nd order corrected
3rd order corrected

Monochromator





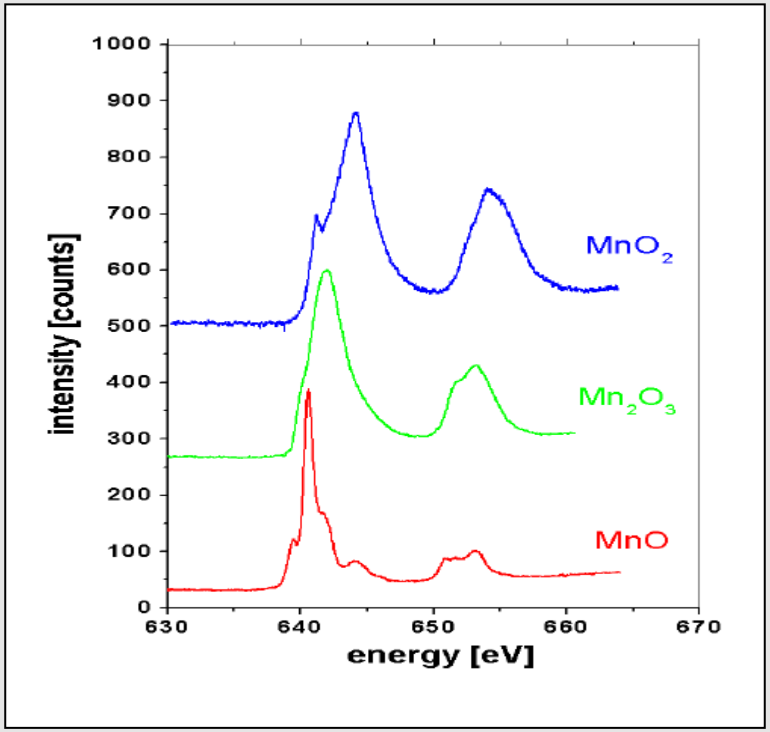


- **Monochromator enabling reduction of beam energy width of Schottky-FEG: FWHM intrinsic 0.7 eV to below 0.1 eV.**
- **Improved lateral resolution for uncorrected TEM, information limit ~ 1 Å.**
- **Improved spectral resolution and imaging: ΔE ≤ 100 meV**
- **Ease-of-use integration without constraints for unfiltered mode**

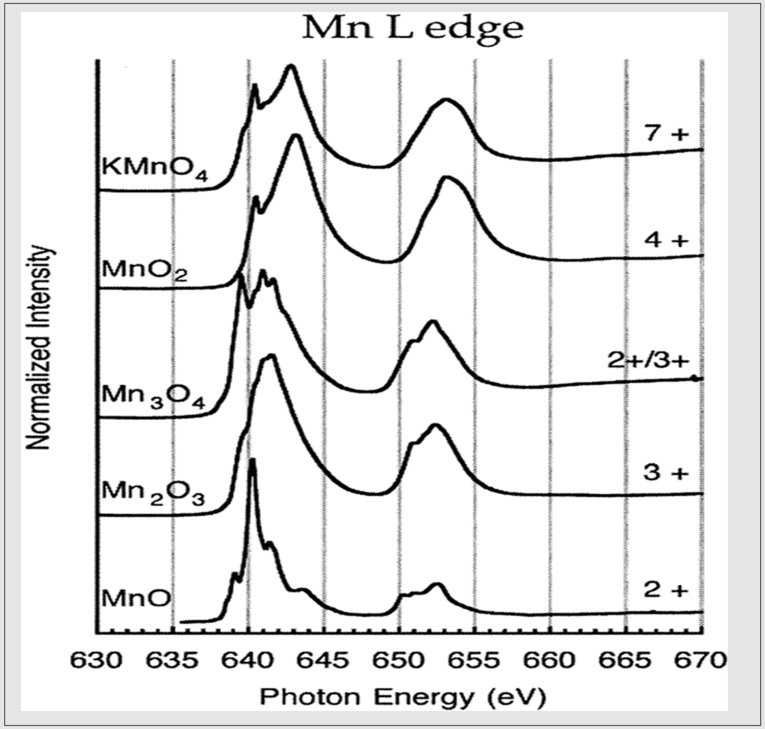
Sub eV Energy Resolution vs. XAS

Electron Loss Near Edge Spectroscopy (ELNES)

X-ray Absorption Spectroscopy (XAS)



Mn-$L_{2,3}$ ELNES acquired by high energy resolution EELS of MnO, Mn_2O_3, and MnO_2 (unprocessed, 4x10s exposure time).



Mn-L XANES acquired by XAS with synchrotron radiation

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Cs/Cc Correctors for SEM

- Cs/Cc correction has great potential for low kV high resolution analysis and metrology of radiation sensitive materials

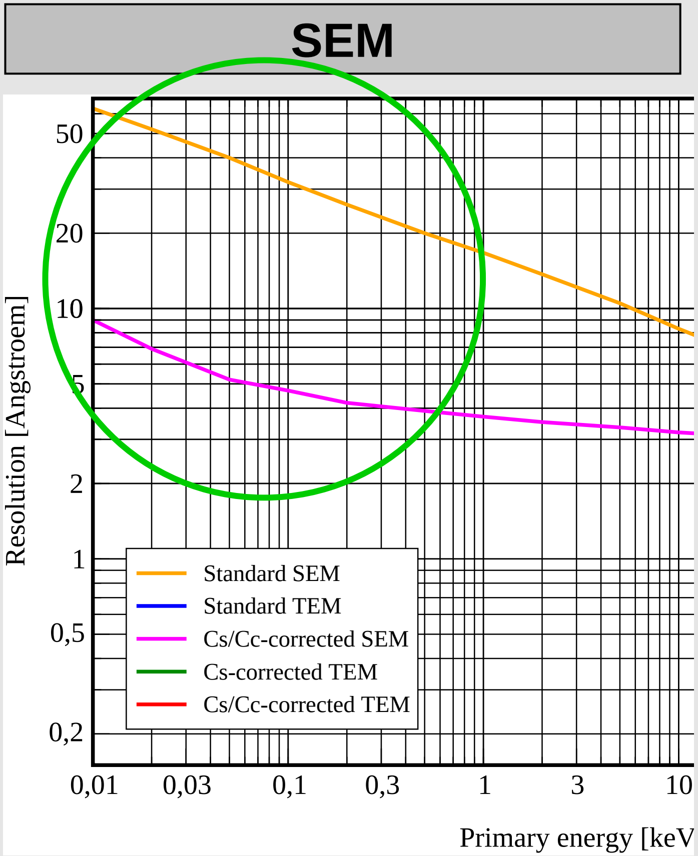
- Low kV microscopy is mandatory for small interaction volume between electron beam and sample resulting in ultimate high resolution surface imaging

<u>Multipole corrector</u>

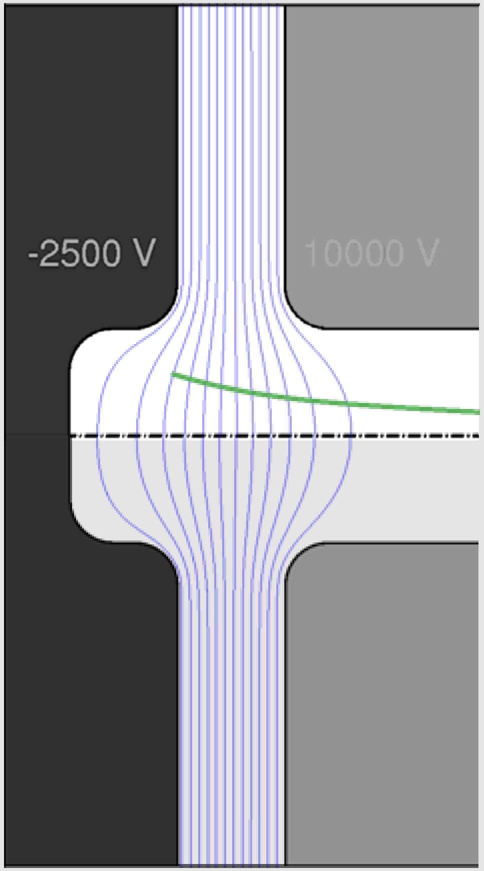
Integration of multipole corrector requires enormous system stability

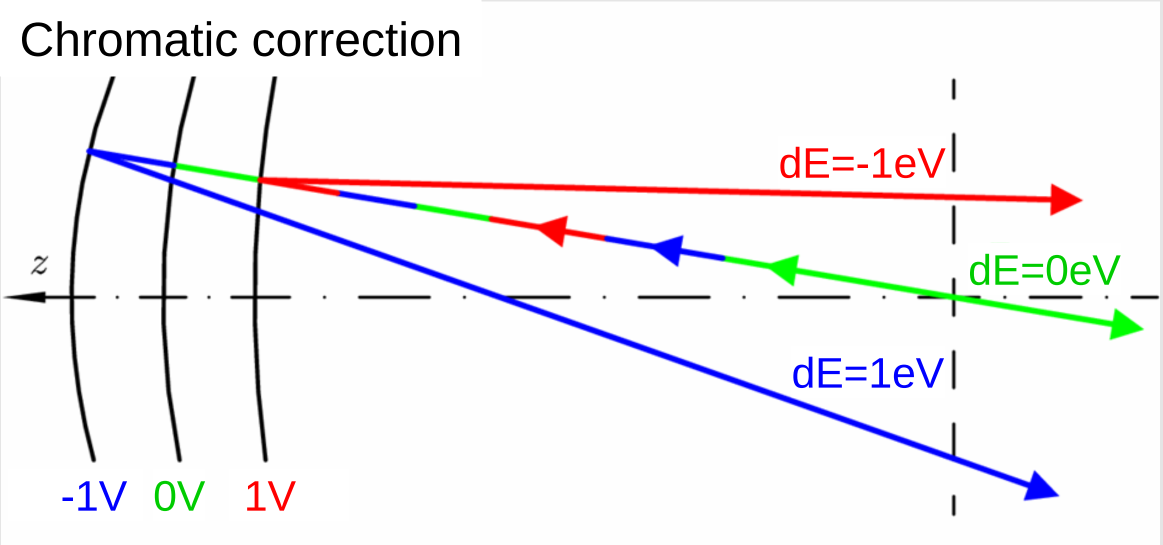
<u>Mirror corrector</u>

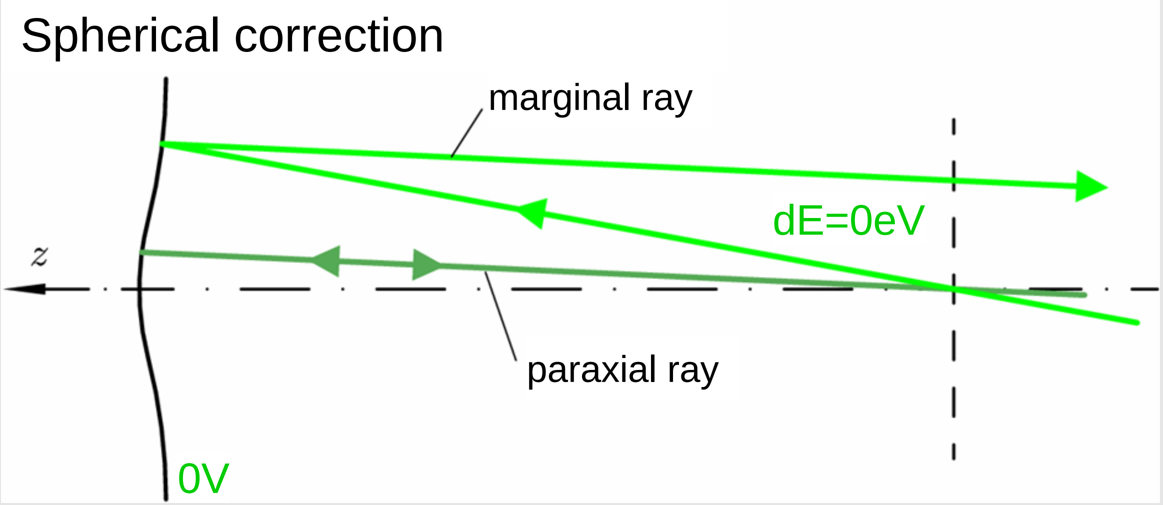
Mirror corrector results in best resolution and has lower electronic stability demands



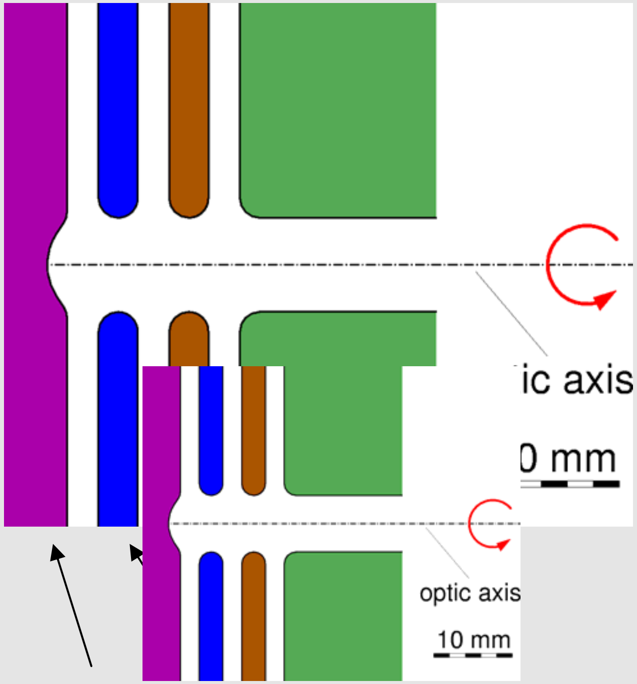
Electrostatic Cs/Cc Mirror Corrector




Chromatic correction


Spherical correction

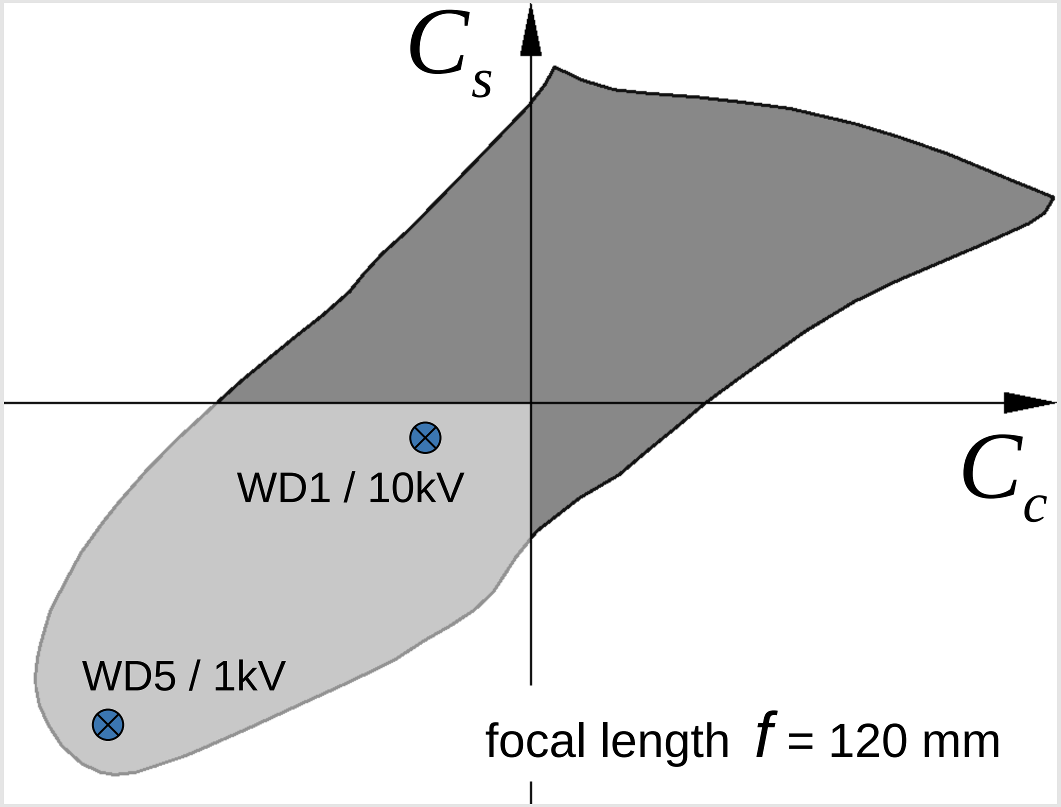
Variation Range of a Tetrode Mirror Corrector



$$V_1 \quad V_2 \quad V_3$$

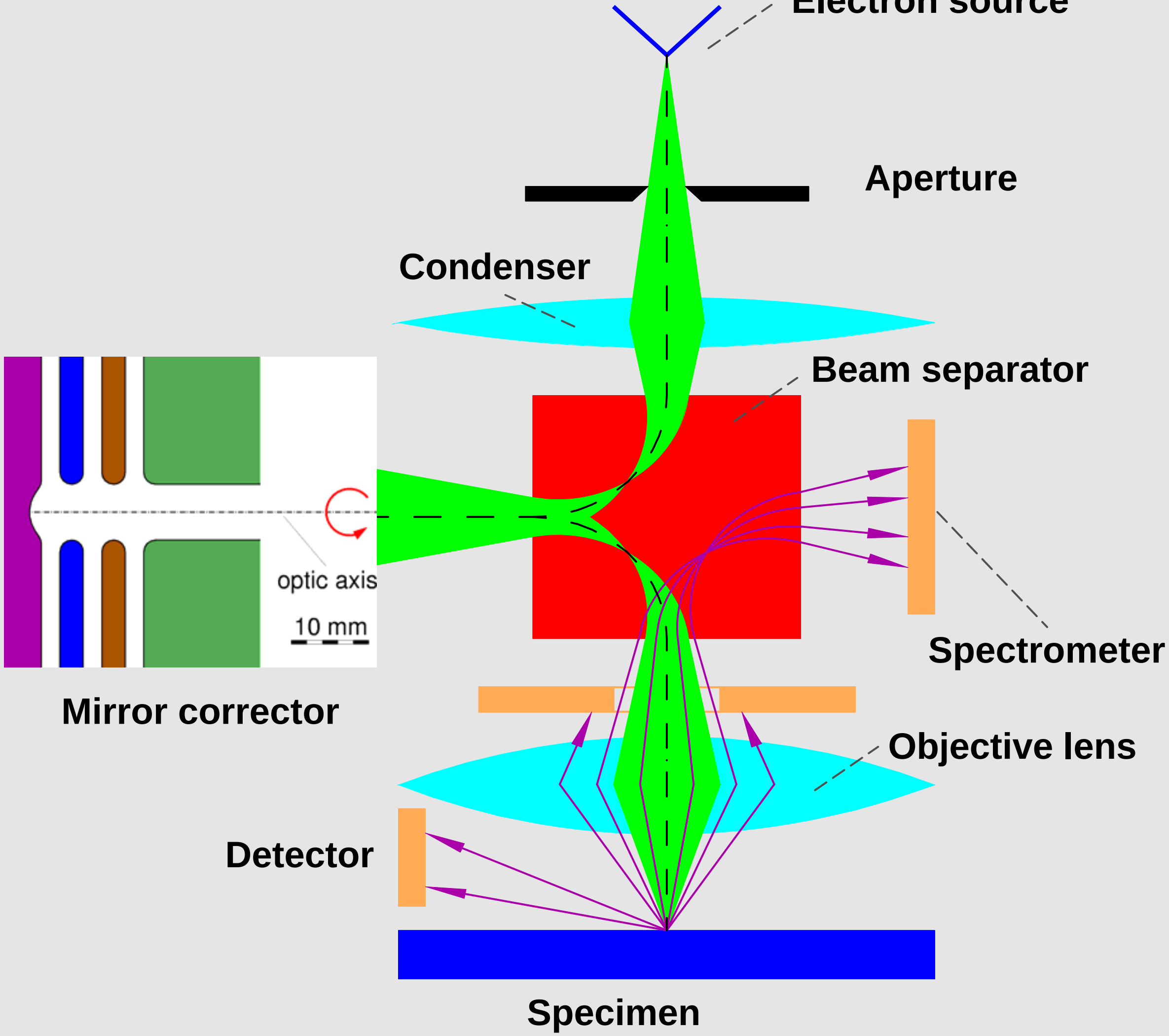
$$\downarrow$$

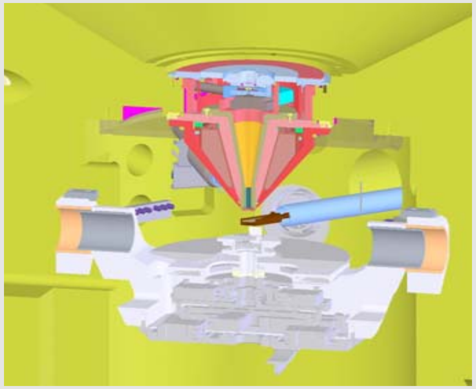
$$f\ , C_c\ , C_s$$



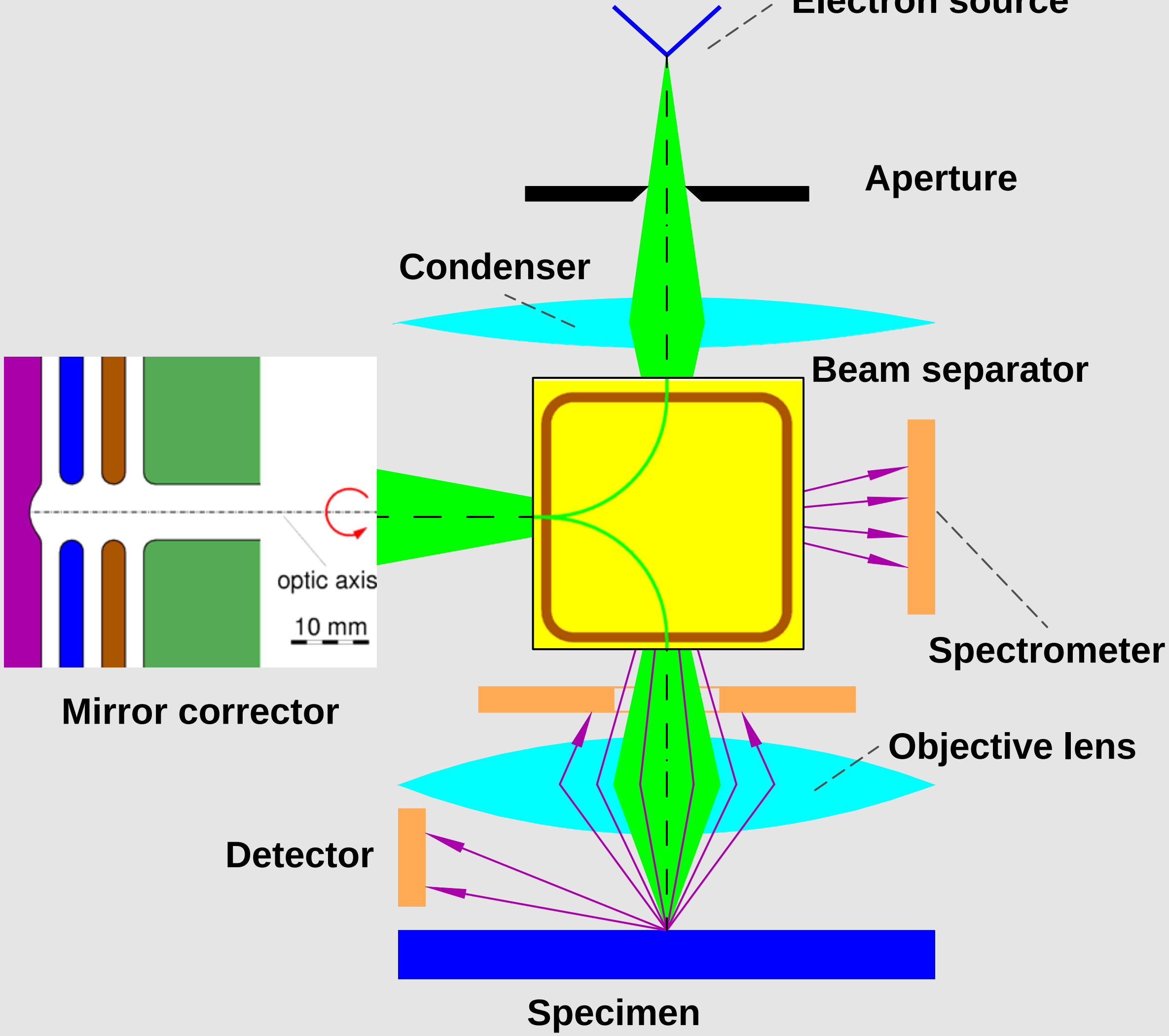
focal length f = 120 mm

Electrostatic Cs/Cc Mirror Corrected SEM

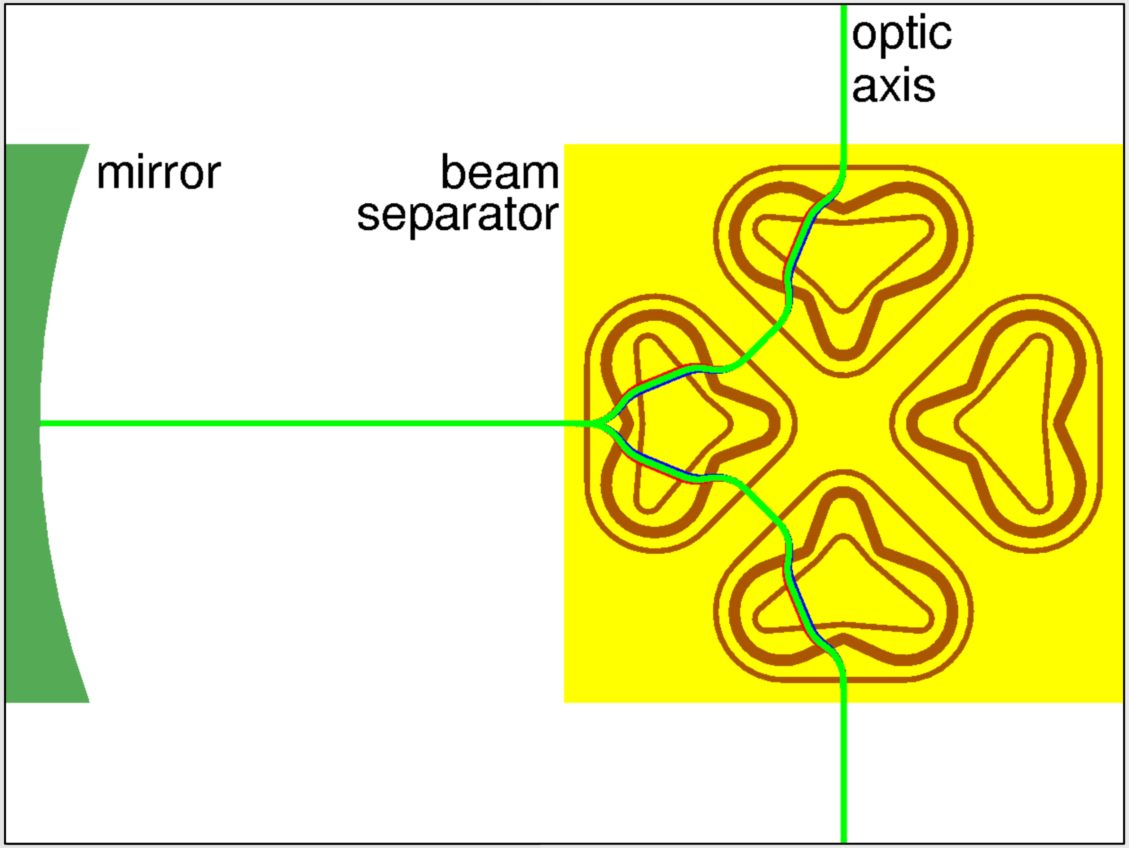




Electrostatic Cs/Cc Mirror Corrected SEM

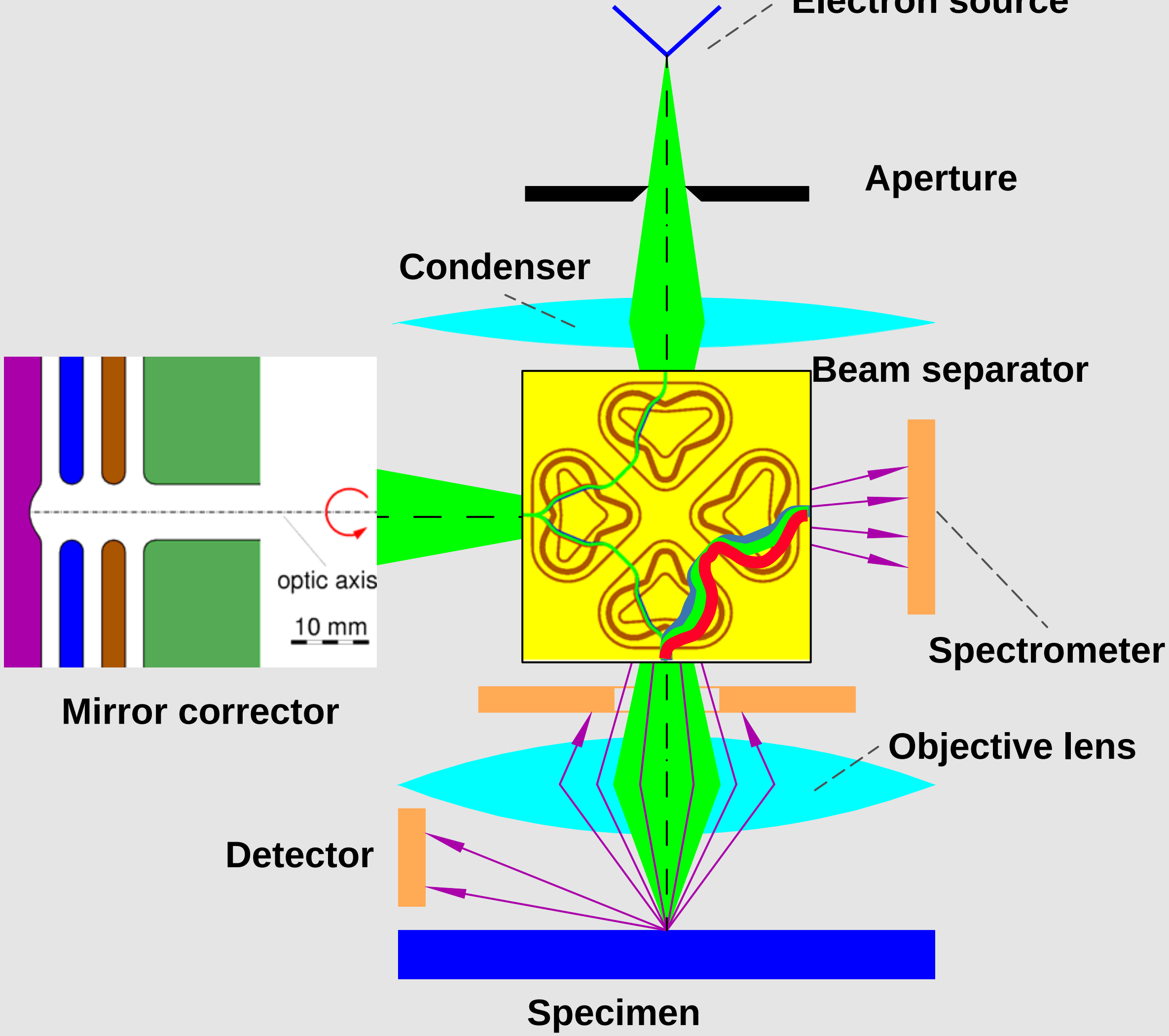


Beam Separator – Primary Beam

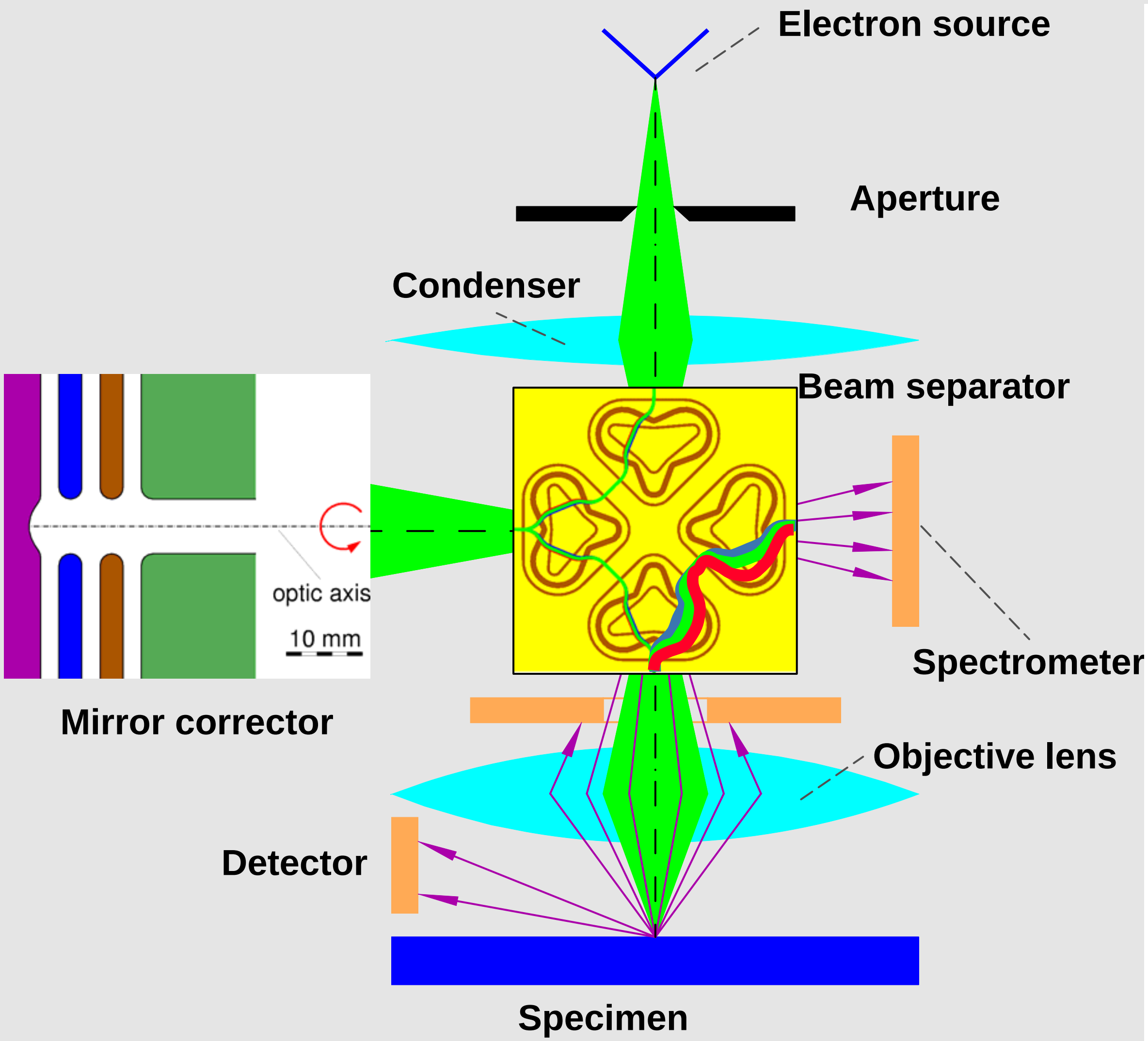


Top view from the mid-plane

Electrostatic Cs/Cc Mirror Corrected SEM



Electrostatic Cs/Cc Mirror Corrected SEM
Monte Carlo Simulation of BSE Contrast Distribution



Potentials of corrected SEM:

- Very low electron energy specimen inspection at ultimate resolution without causing radiation damage
- Minimized interaction volume results in high resolution surface imaging
- Beam separator enables implementation of new analysis capabilities (e.g. electron spectroscopy) without interfering the primary beam
- highly productive, large area & ultimate resolution 3D reconstruction in combination with milling device

Summary
Advantages of Corrected Electron Optics

Corrected Element	Productivity	Resolution	Analytics	System
Energy filter	In-column filter		EELS, ESI	TEM
Monochromator	In-column filter	Decrease of energy spread	ELNES	TEM
Multipole Corrector Cs	Increased current enlarged aperture α	Spherical aberration Point resolution down to information limit	No de-localization Phase contrast microscopy	TEM
Multipole Corrector Cs/Cc	Enlarged analytical gap of objective lens	Chromatic aberration Low energy TEM	Imaging of multiple scattered electrons Short depth of focus Single atom spectroscopy	TEM / SEM
Mirror Corrector Cs/Cc	Increased current No specimen preparation in comparison to TEM	Chromatic aberration Ultra low energy SEM	Enhanced contrast Low voltage contrast	SEM
Beam splitter	Enhanced signal to noise	Prerequisite for mirror corrector	Secondary electron spectroscopy	SEM