Advanced EELS Applications In Process Development

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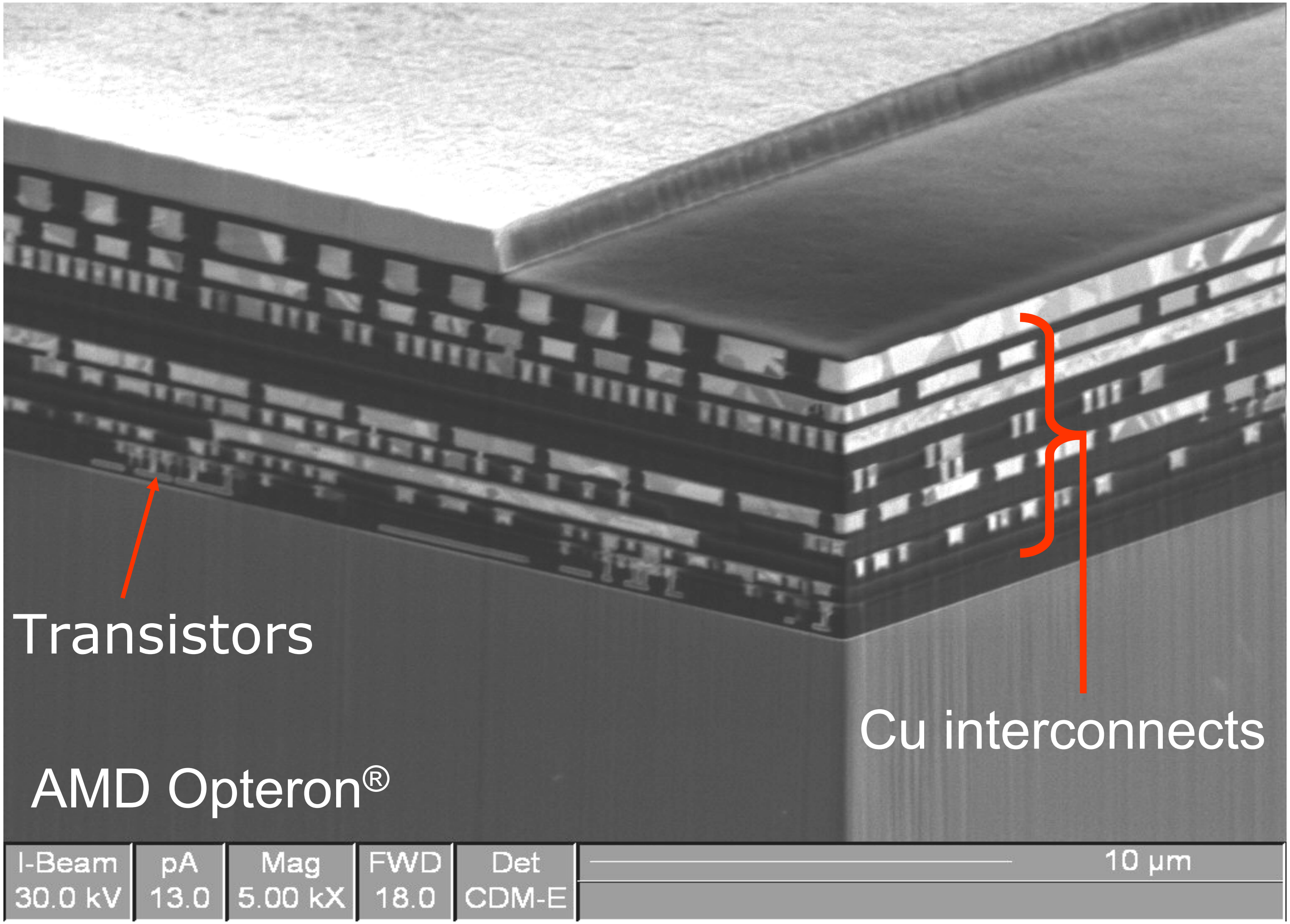
Microprocessor (FIB cut)

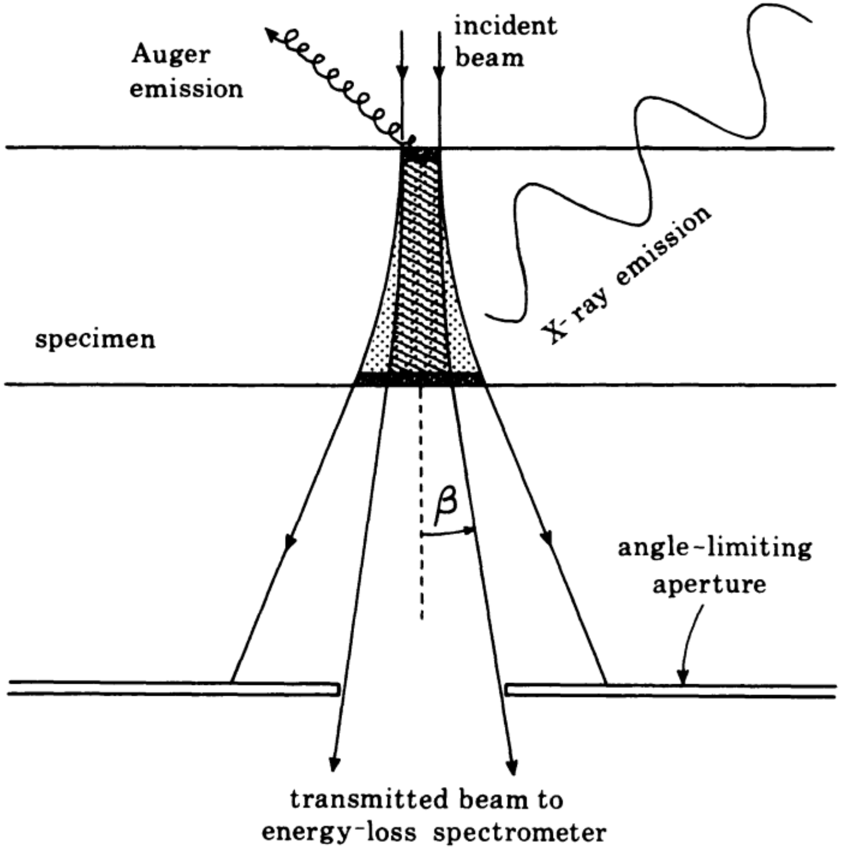


Outline

- Introduction to EELS in the transmission electron microscope
- Element mapping using electron spectroscopic imaging
- Quantitative EELS of advanced gate dielectrics
- Quantitative EELS of low-κ intermetal dielectrics
- ELNES analysis of low-κ intermetal dielectrics and nickel silicides

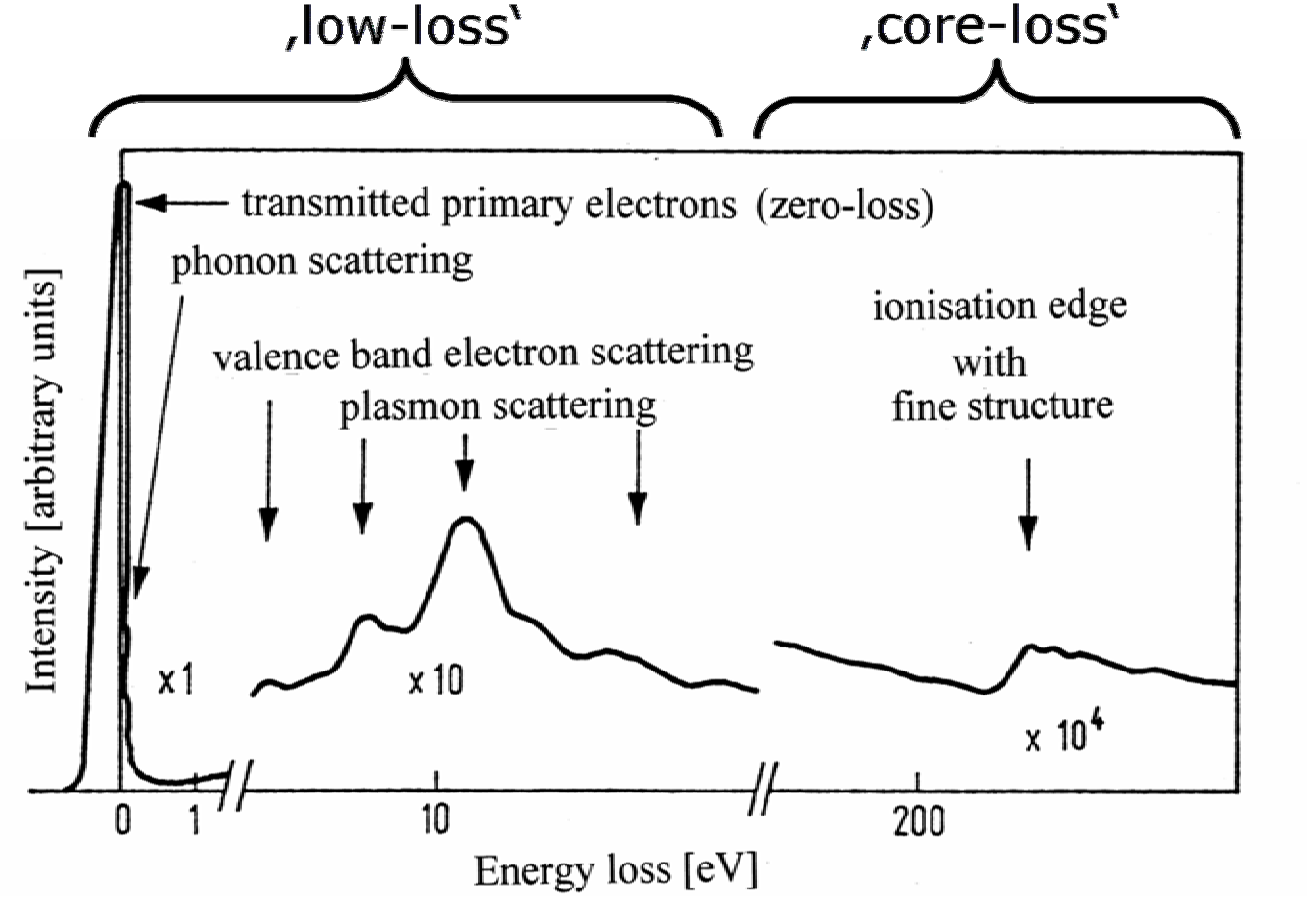
EELS in the transmission electron microscope

Electron beam – specimen interaction



Electron energy-loss spectroscopy (EELS) detects inelastic interactions of beam electrons with the atomic electrons of the probed sample volume

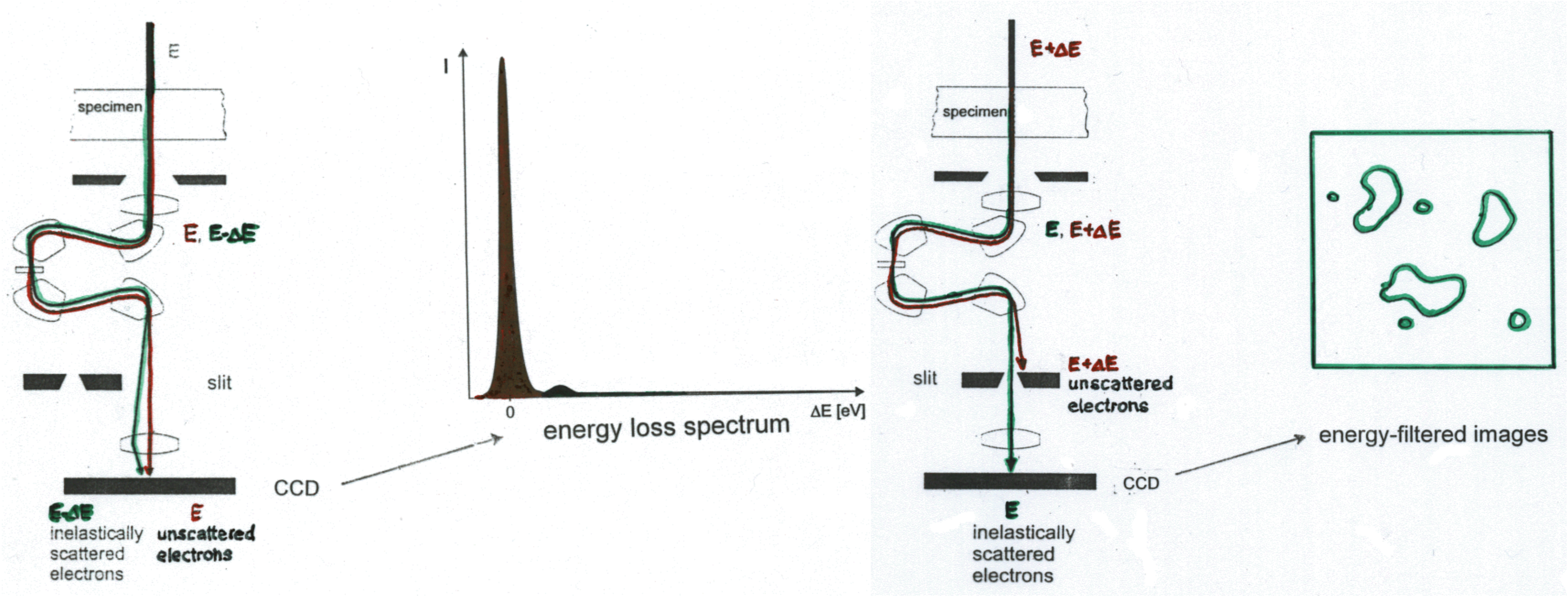
Electron energy-loss spectrum



- Plasmon excitation peaks → **Dielectric material properties**
- Core ionization edges → **Compositional analysis**
- Core ionization near-edge structure (ELNES) → **local atomic environment, chemical bonding**

Electron energy-loss spectroscopy in the TEM

Imaging energy filters allow to record spectra and energy selective images



- •spatial resolution limited by the size of the focused electron probe
- •energy resolution limited by the energy width of the electron source

- •spatial resolution limited by filter optics
- •energy resolution limited by the width of the energy selecting slit

Current performance standards

Field emission gun (FEG), highly stable microscope electronics

→ **sub-nanometer electron probes**

Aberration correction of the probe forming electron optics

→ **high SNR** or **sub-Angstrom electron probes**

Corrected spectrometers

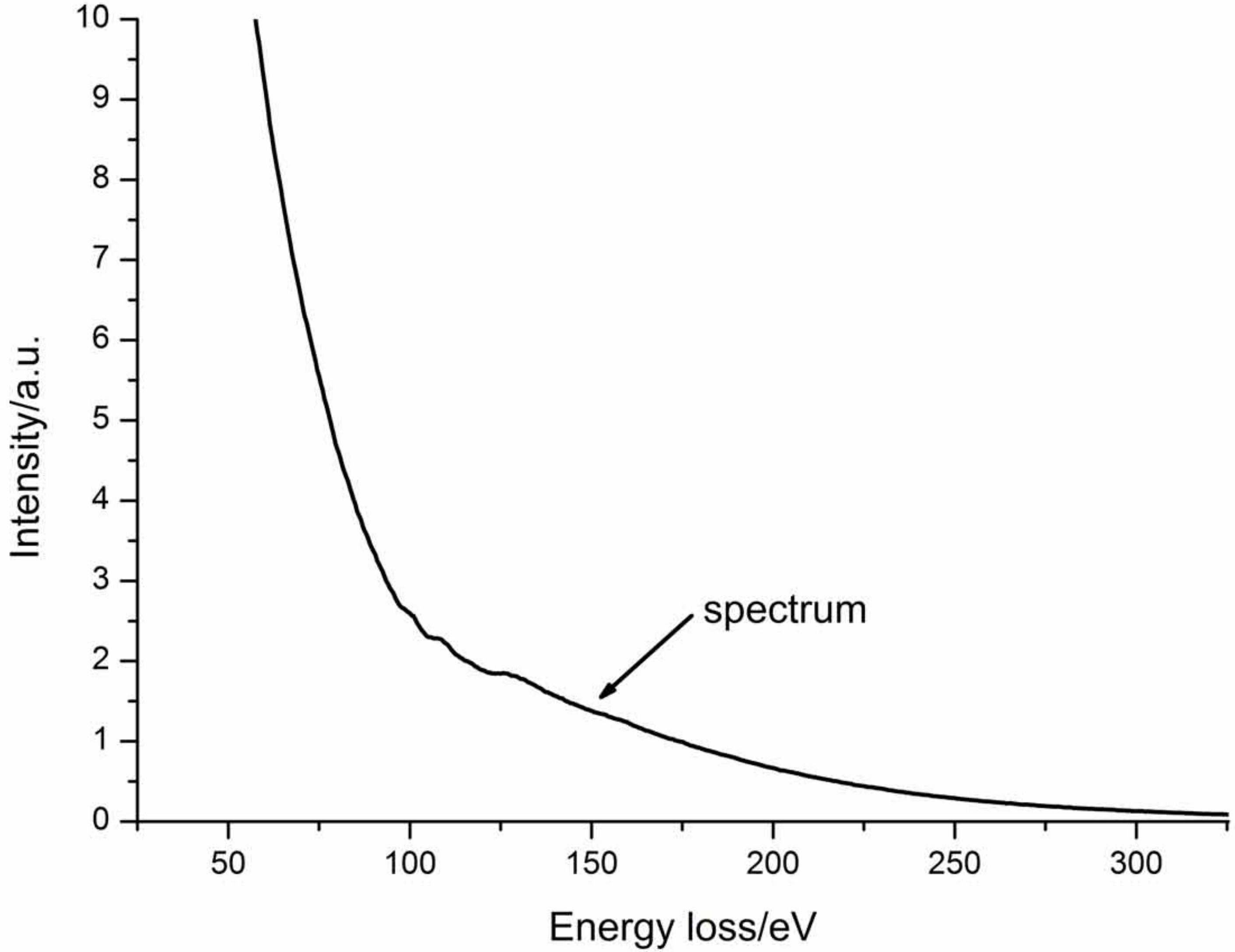
→ **energy resolution limited by the energy width of the electron source**

(Standard Schottky FEG: 0.5–1 eV,

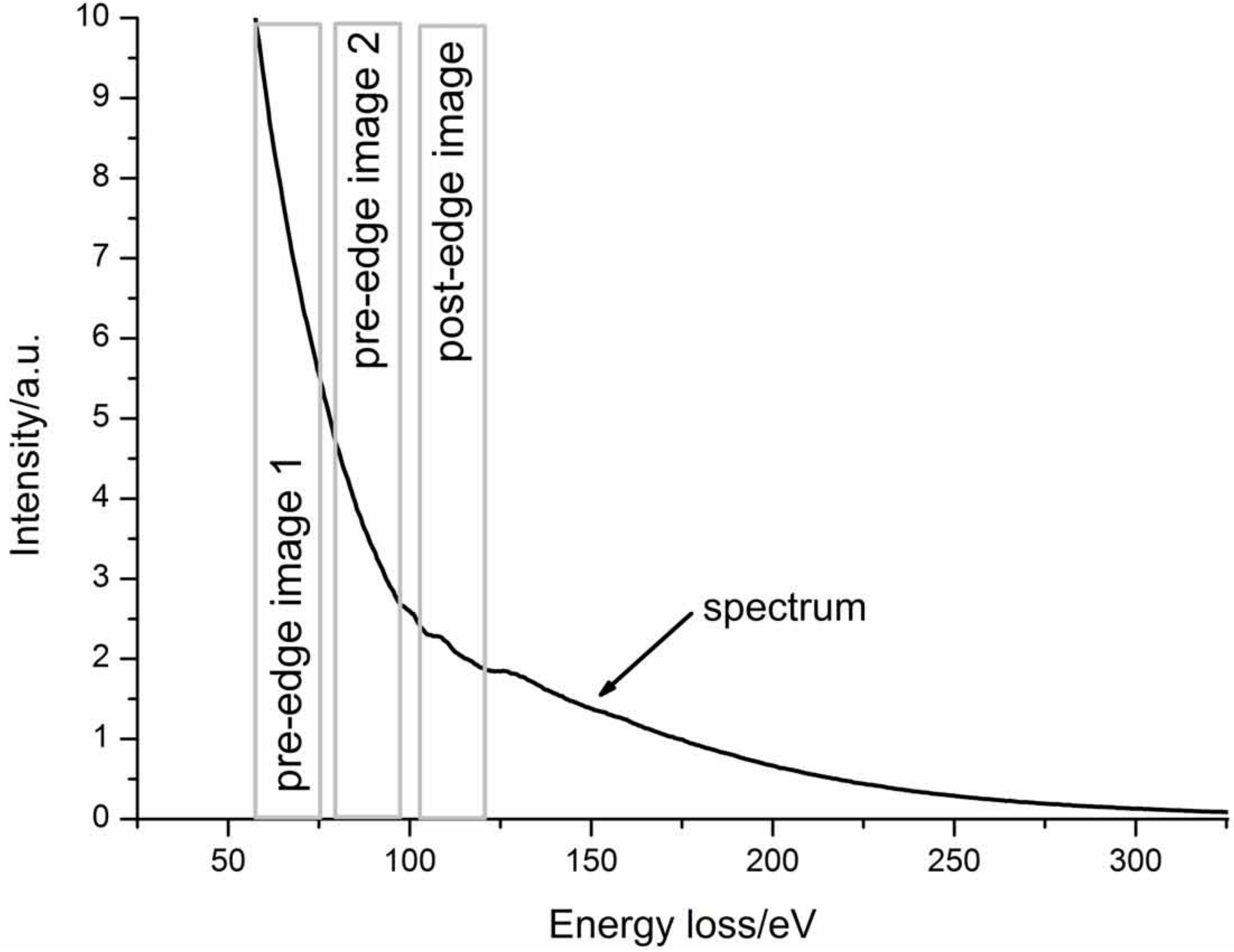
Monochromated FEG: 0.1-0.3 eV)

Element mapping using Electron Spectroscopic Imaging (ESI)

Element mapping using the three-window method



Element mapping using the three-window method



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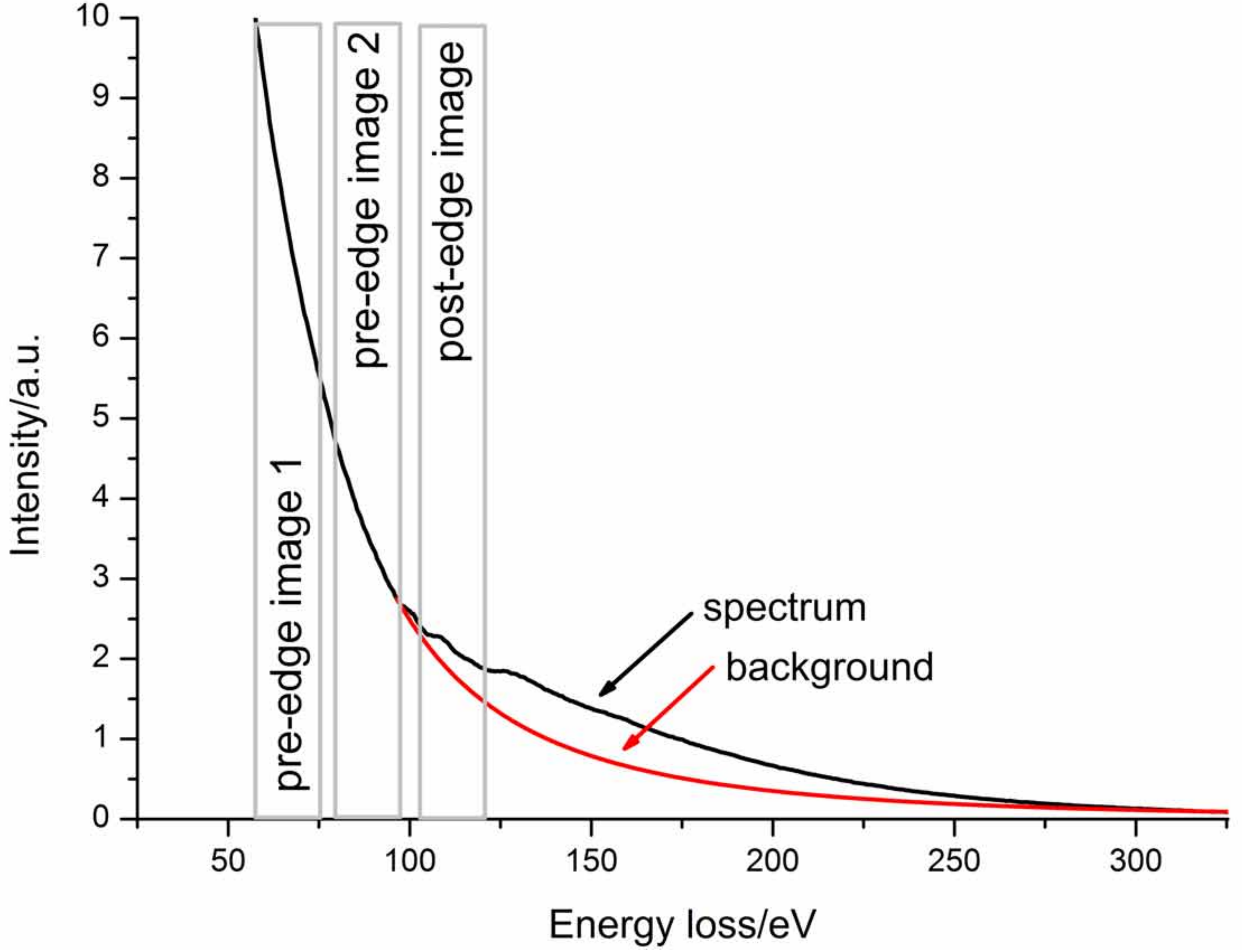

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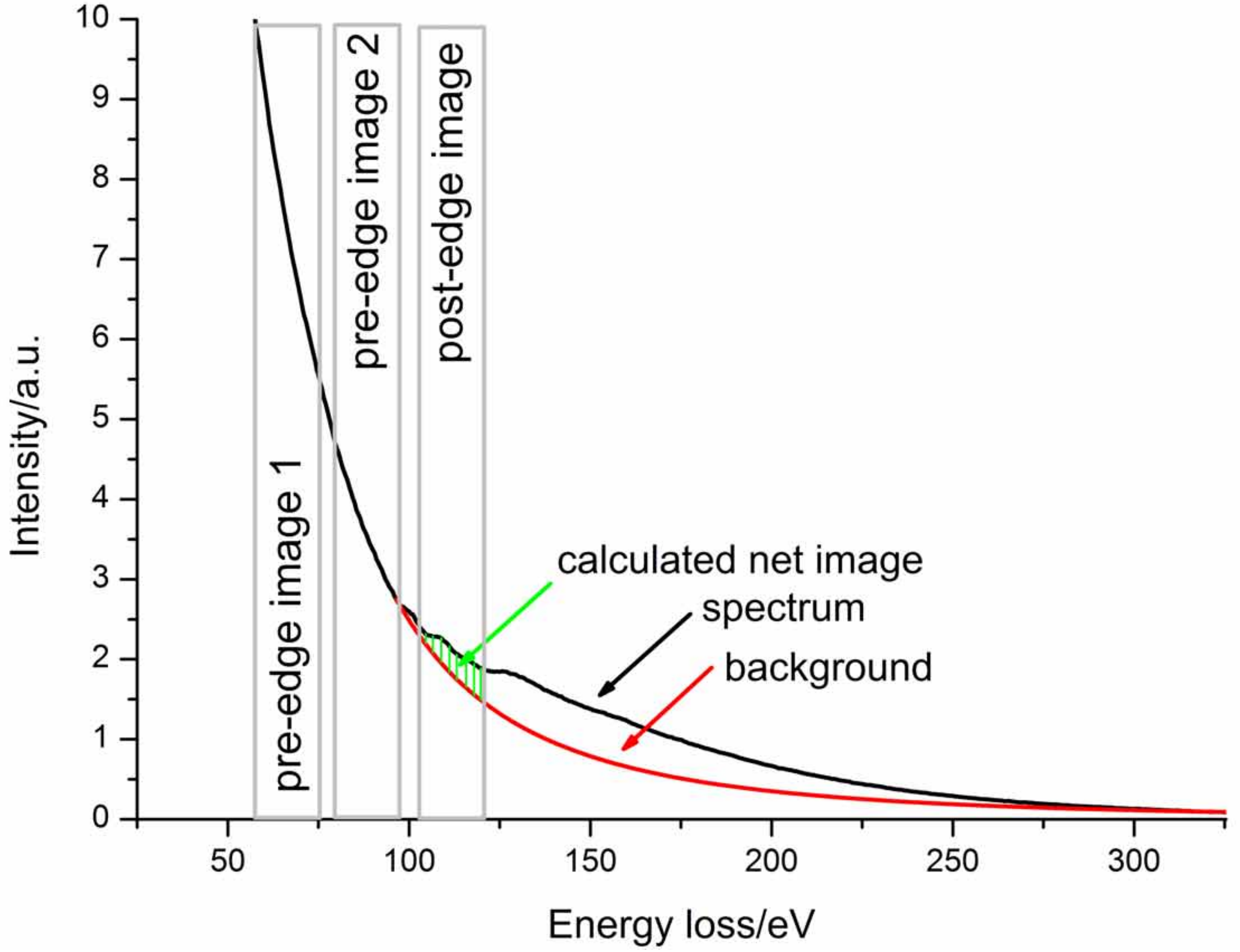
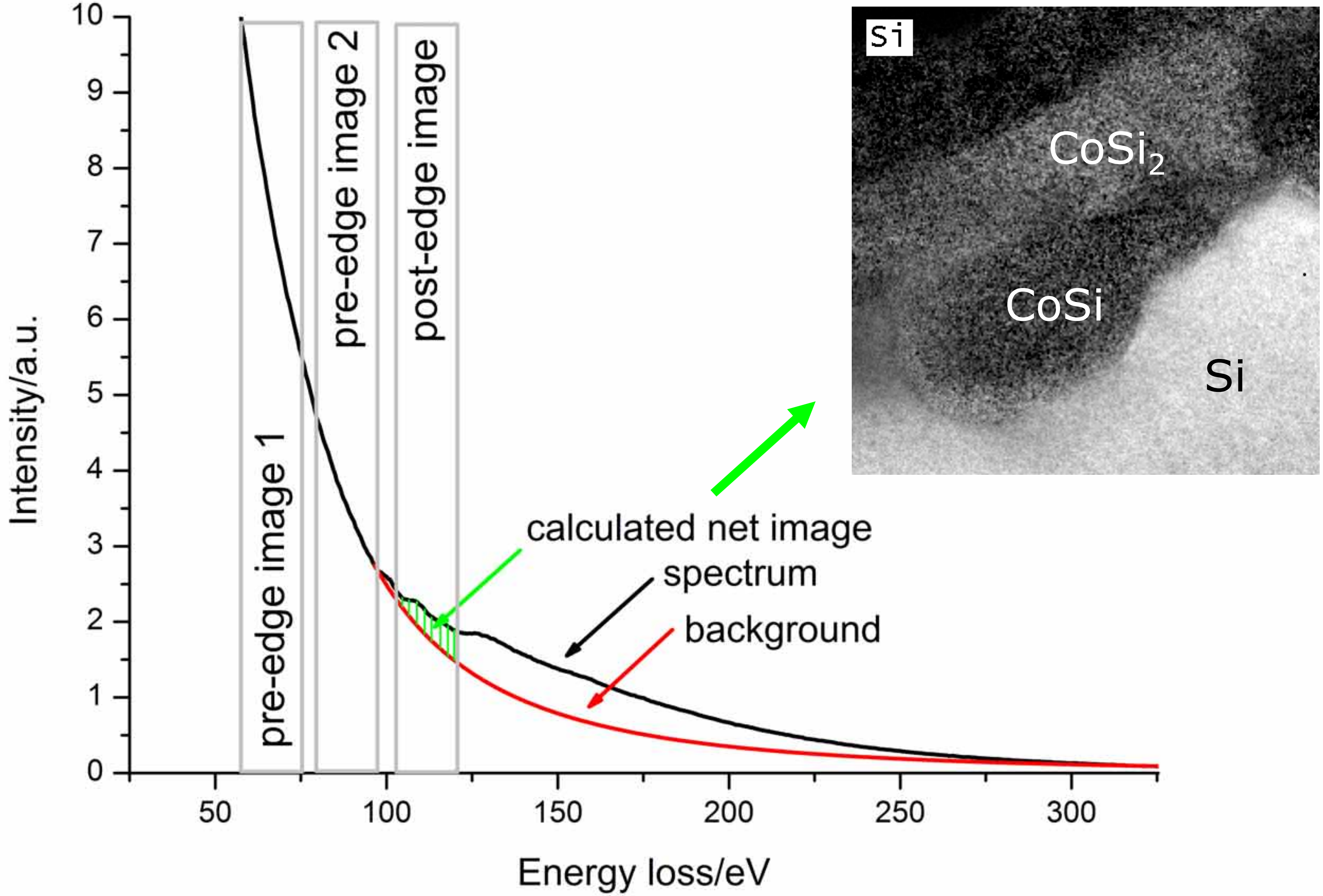


Element mapping using the three-window method



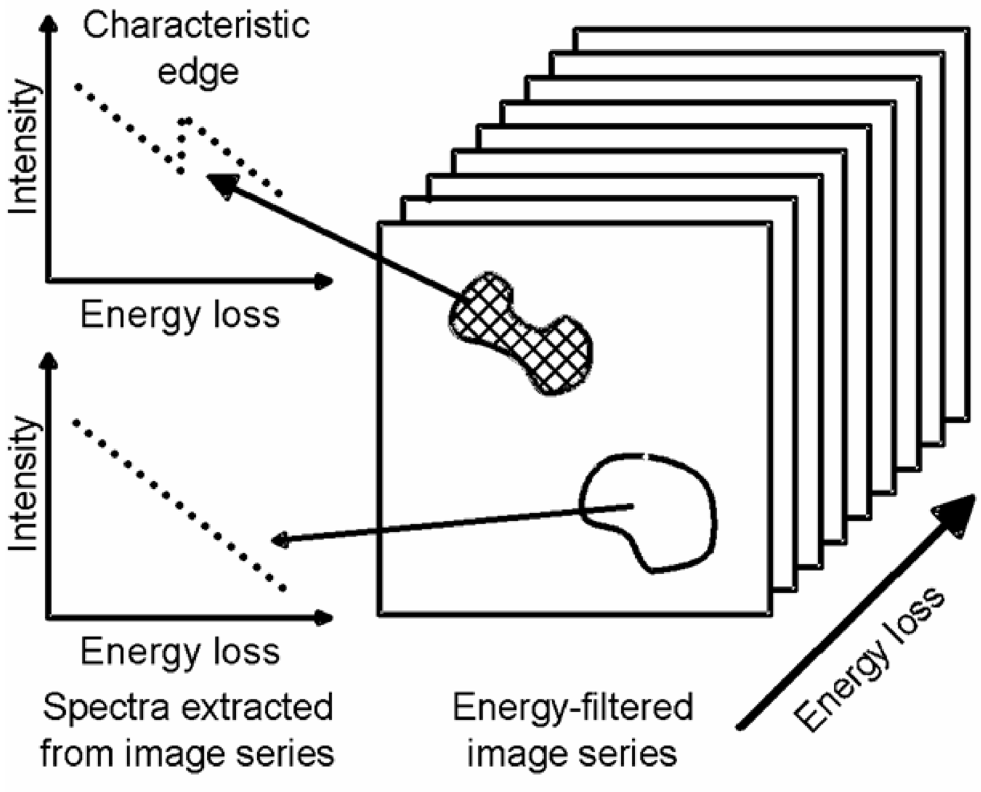
Element mapping using the three-window method

- Three-window method is routinely used for physical failure analysis at specific sites (e.g., identifying etch residuals or contaminating particles)
- Results depend on the quality of the edge background extrapolation - user has little control over this process
- Detection of low concentrations unreliable

→ **It is often preferable to examine an actual spectrum from a region of interest**

→ **use Image-EELS**

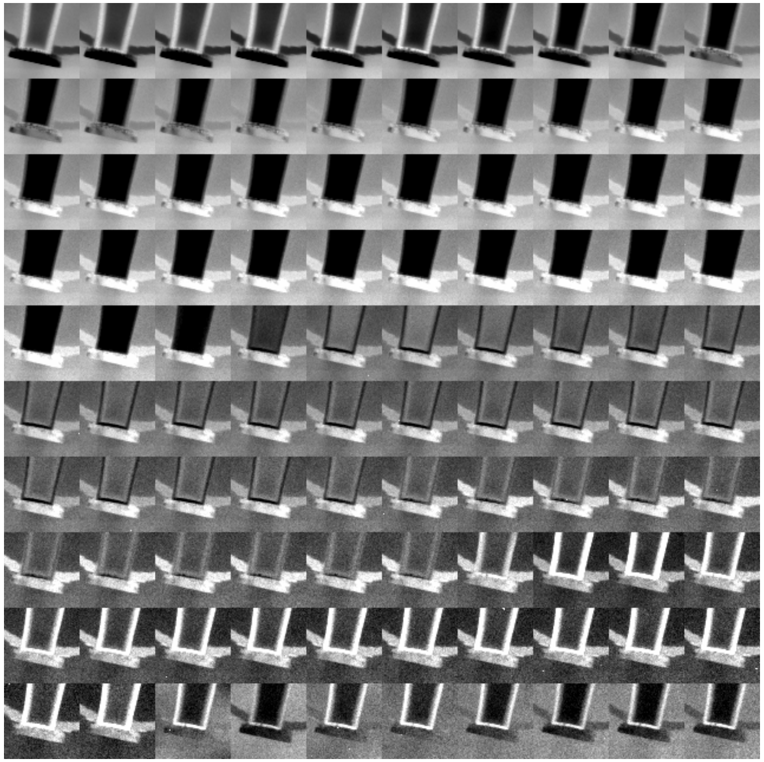
Principle of Image-EELS



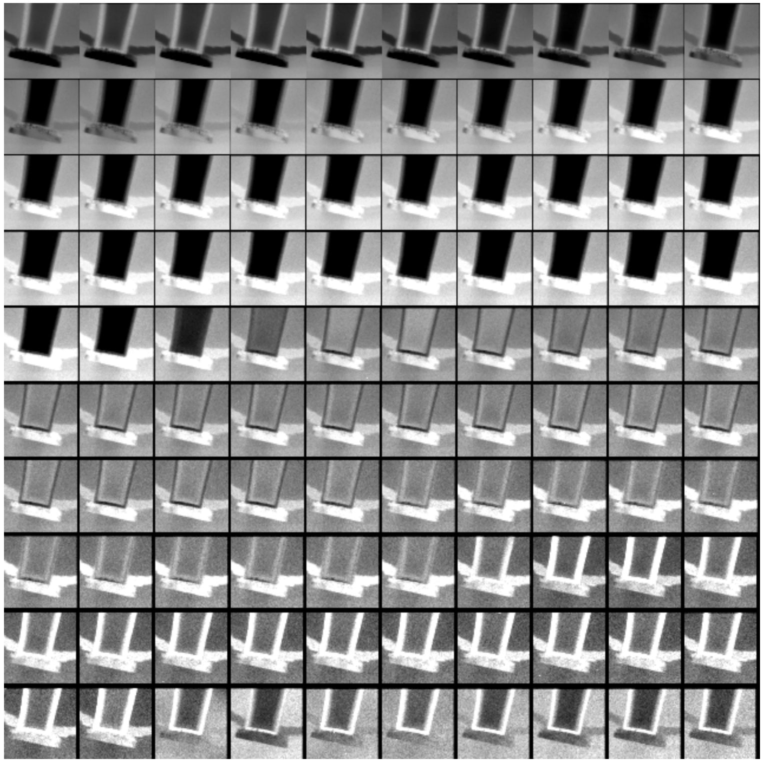
Record a series of energy-filtered TEM images and extract spectra from any desired region of interest

Image-EELS of an SOI contact after TiN barrier deposition

- Cross-section prepared by FIB cutting
- 100 images in 5 eV-steps (80-575 eV), energy slit width 5 eV, 4 s/image.
- Specimen drift during acquisition corrected off-line by cross-correlation image alignment

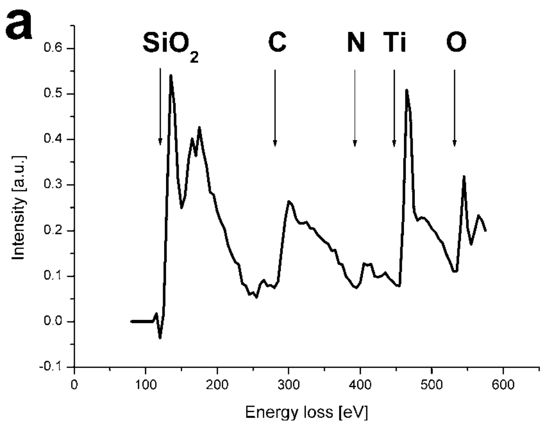


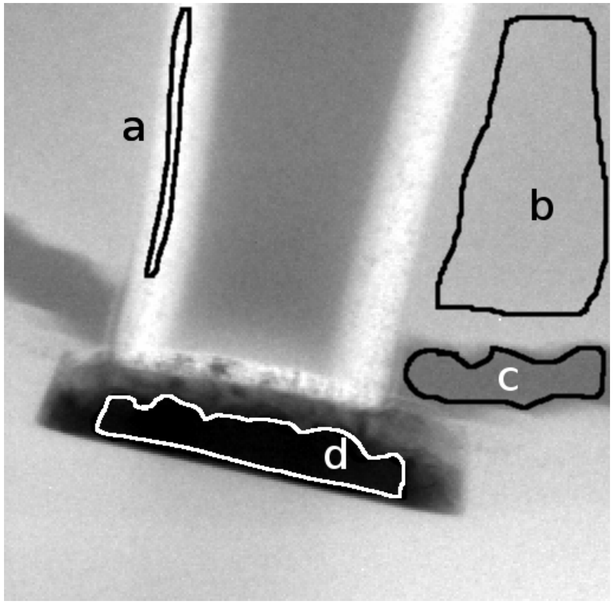
Raw data

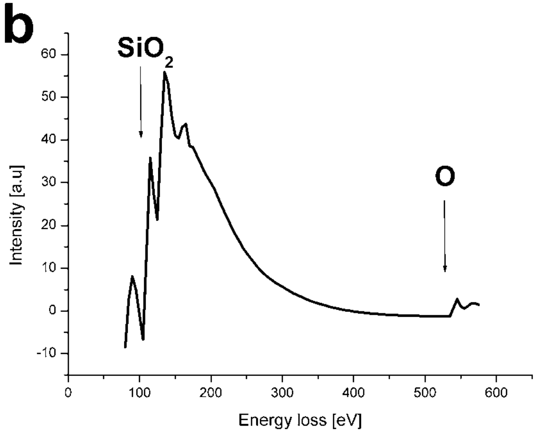


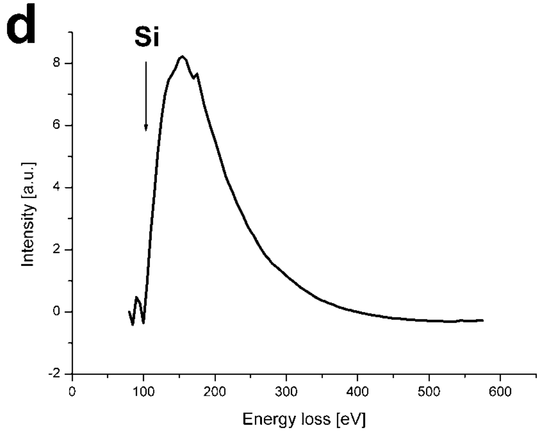
After alignment

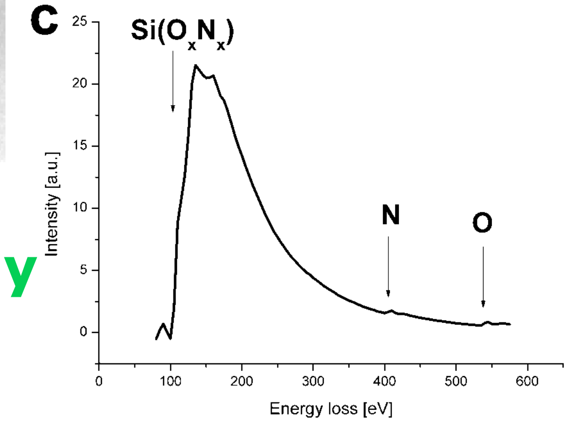
Image-EELS of an SOI contact after TiN barrier deposition









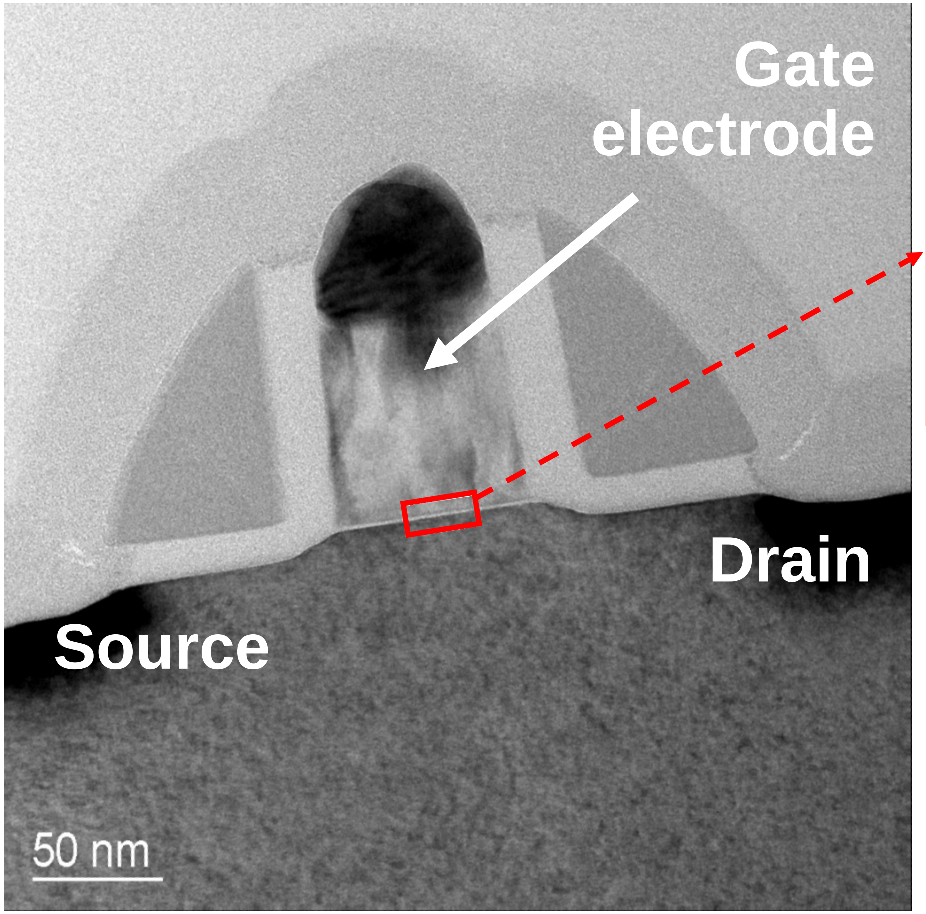


Compositional analysis of arbitrarily shaped regions of interest

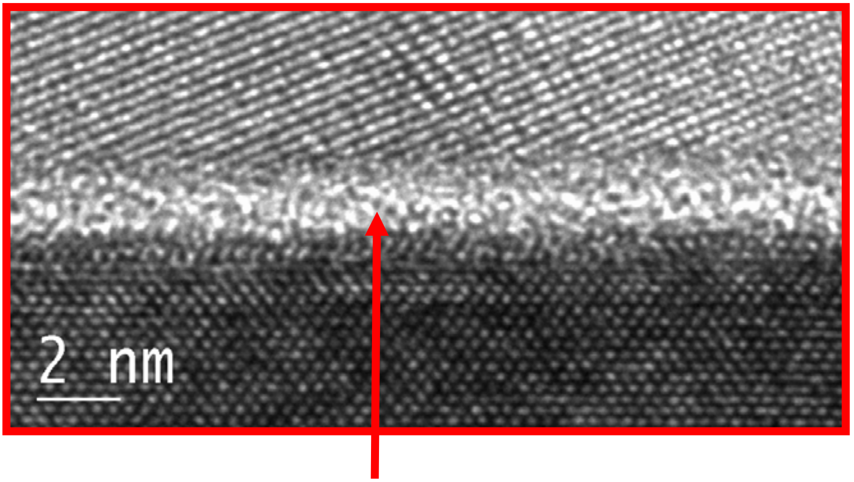
- Abnormal features (e.g., residual layers) can be investigated in detail
- Characteristic near-edge structures of the Si-$L_{2,3}$ edge can be distinguished

Quantitative EELS of advanced gate dielectrics

MOSFET with nitrided gate oxide



TEM of a MOSFET

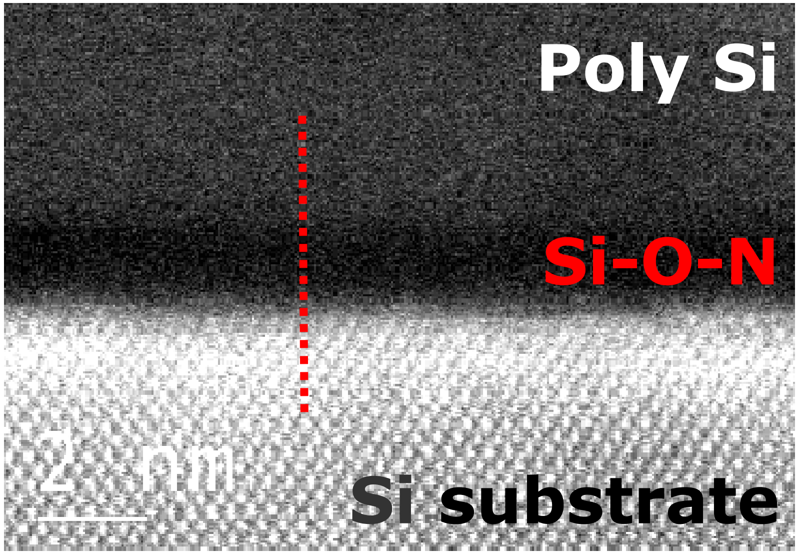


- Si-O-N gate dielectric - less than 10 atomic layers!
- The N distribution affects the properties of the Si-O-N layer

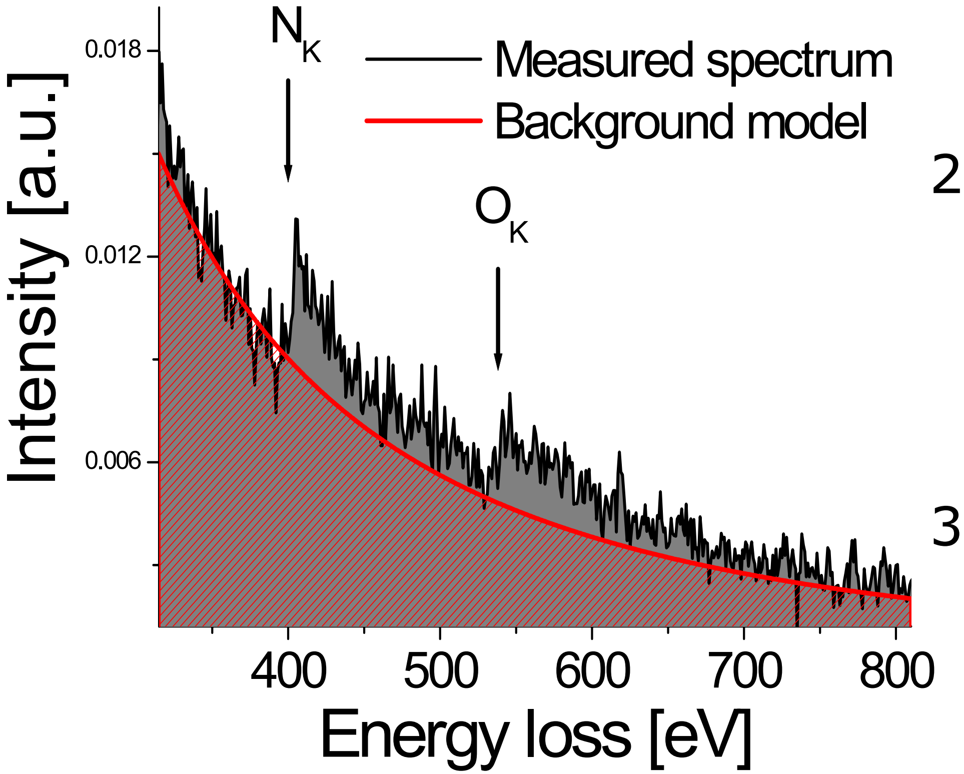
→ **N distribution in the 5-15 at% range can be measured by EELS at sub-nanometer resolution**

EELS line scans across the gate dielectric

- Si-O-N deposited by plasma-enhanced CVD
- Specimen thickness 20-80 nm
- Electron probe size ≈ 0.35 nm
- Line scans: 40 points in 0.15 nm steps across the gate dielectric
- Max. 1-2 s per point due to specimen drift



Conventional quantitative spectrum processing



1. Model the edge background ($\propto E^{-r}$). NOT GOOD FOR OVERLAPPING EDGES!
2. Area under the edges is proportional to the concentrations per area, BUT ONLY FOR SINGLE SCATTERING!
3. Differential scattering cross-sections needed for quantification. PROBLEM: THEORETICAL CROSS-SECTIONS INACCURATE!

Improved spectrum processing by reference spectra fitting

Decomposition of the measured spectrum into its single, double,... scattering components:

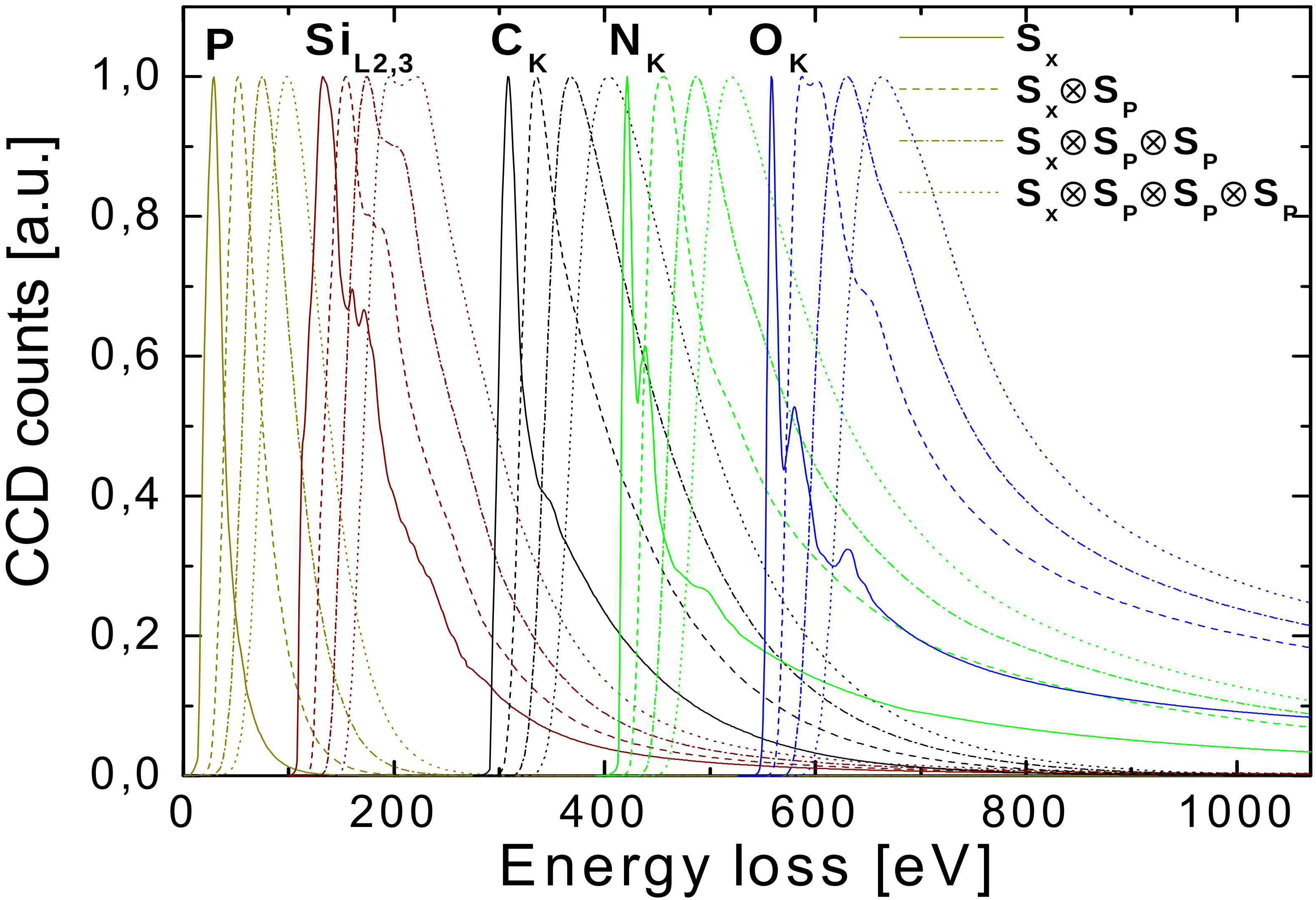
$$\begin{aligned}\text{Fit} = {} & P_1 S_P + P_2 S_P \otimes S_P + P_3 S_P \otimes S_P \otimes S_P + \cdots \\ & + Si_1 S_{Si} + Si_2 S_{Si} \otimes S_P + Si_3 S_{Si} \otimes S_P \otimes S_P + \cdots \\ & + N_1 S_N + N_2 S_N \otimes S_P + N_3 S_N \otimes S_P \otimes S_P + \cdots \\ & + O_1 S_O + O_2 S_O \otimes S_P + O_3 S_O \otimes S_P \otimes S_P + \cdots\end{aligned}$$

→ Atomic ratios: $N_N/N_{Si} \propto N_1/Si_1$; $N_O/N_{Si} \propto O_1/Si_1$

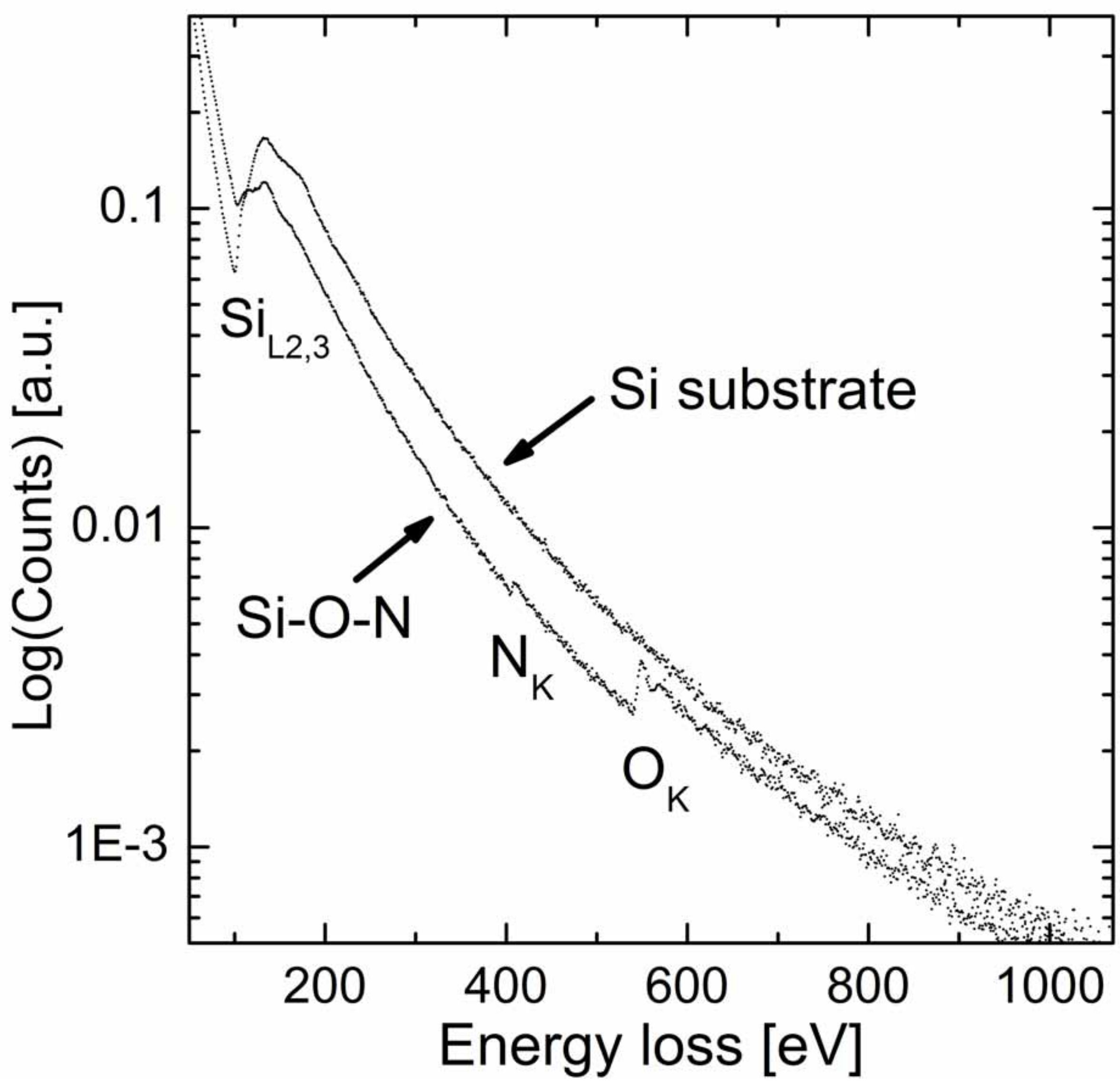
Determine the proportionality factors from calibration measurements

→ **Edge background modelling, removal of multiple scattering effects, separation of overlapping edges, and quantification in a single workstep!**

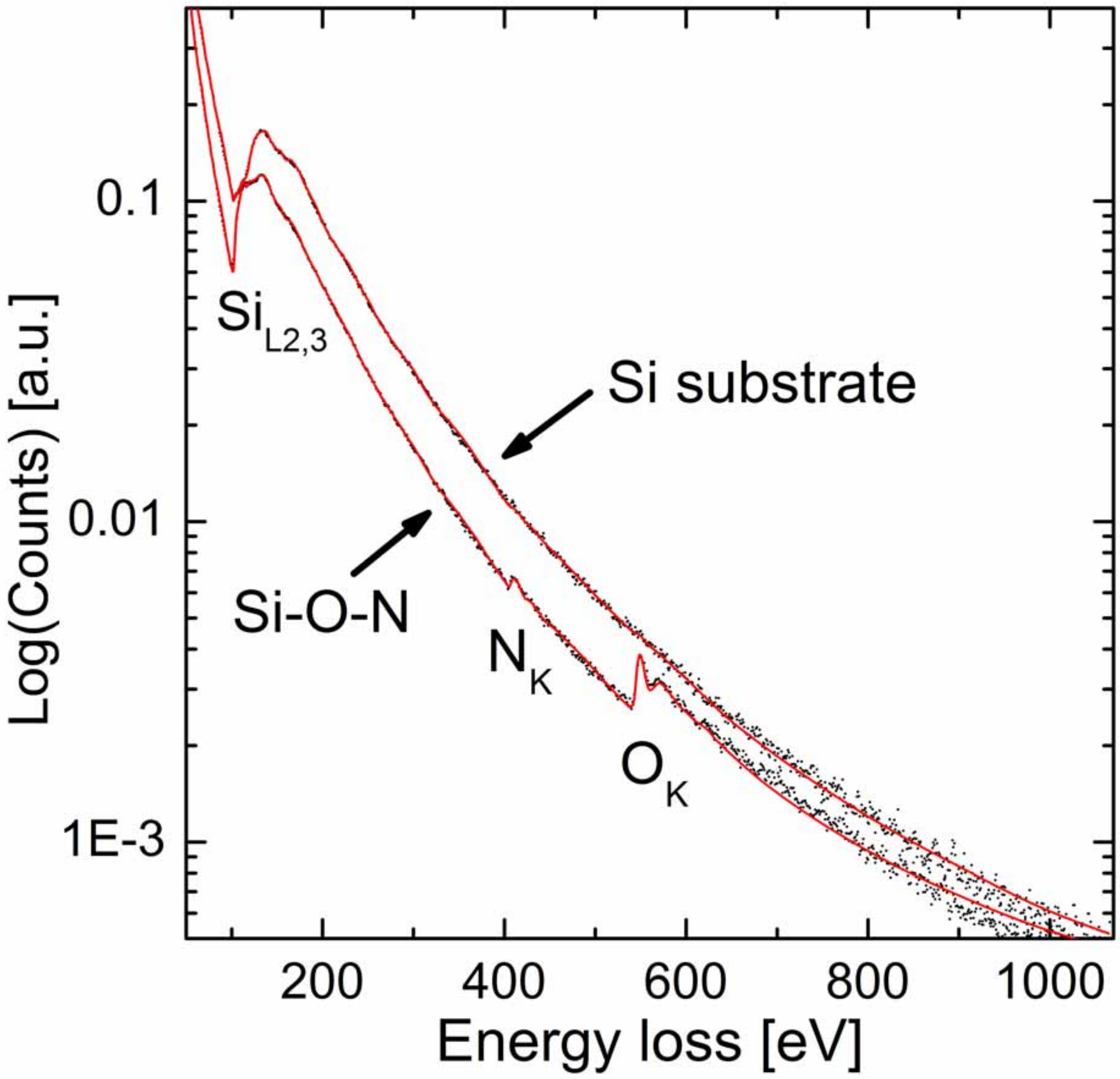
Set of reference spectra



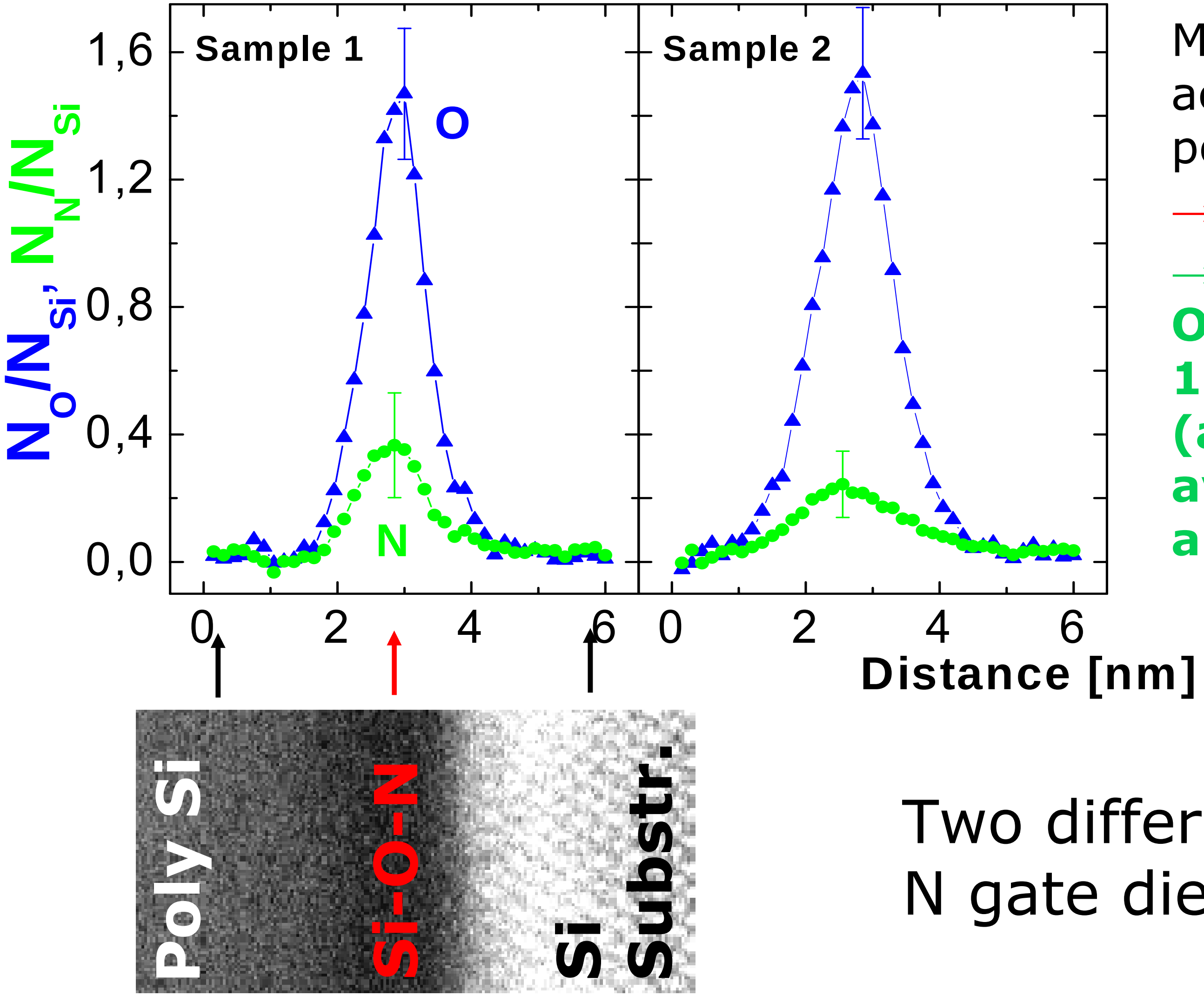
Example fits of two spectra



Example fits of two spectra



Result: spatially resolved atomic ratios of N, O and Si



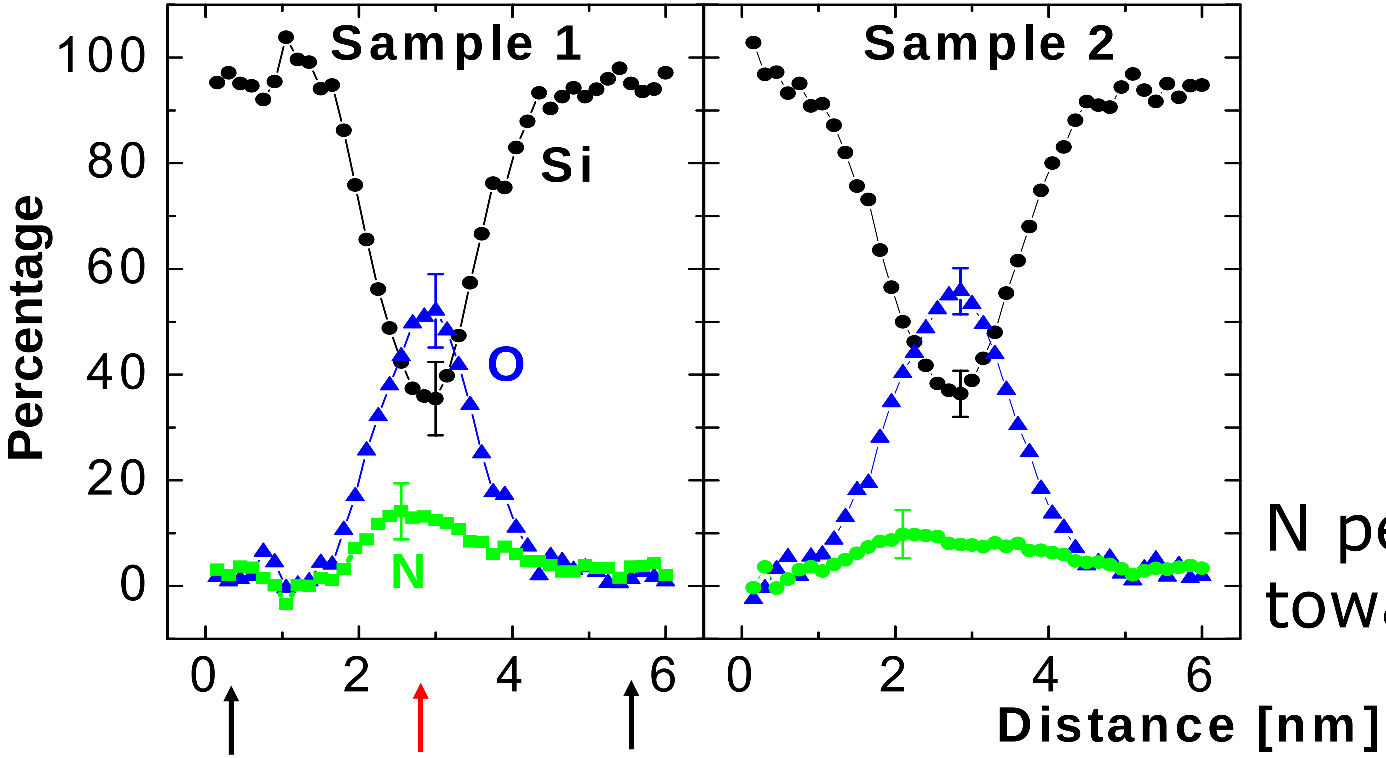
Max. 1-2 s acquisition time per point

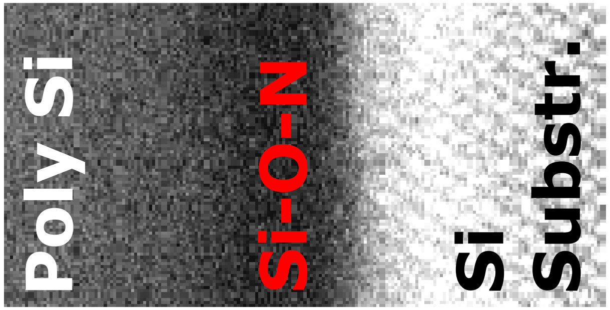
→ **low SNR**

→ **average N- and O- profiles from 10-20 linescans (aligning and averaging automated)**

Two different Si-O-N gate dielectrics

Atomic percentages calculated from the atomic ratios



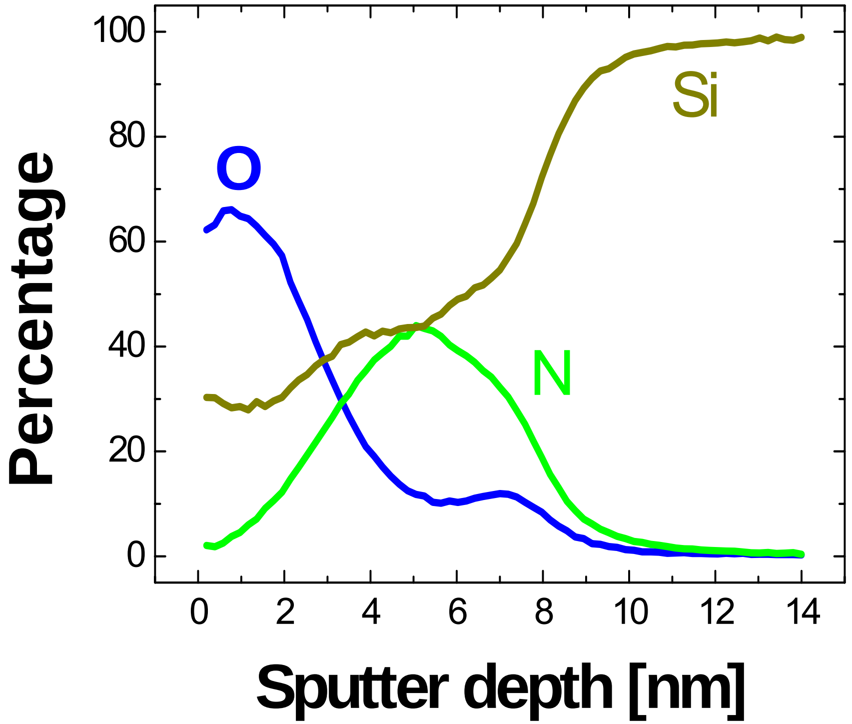


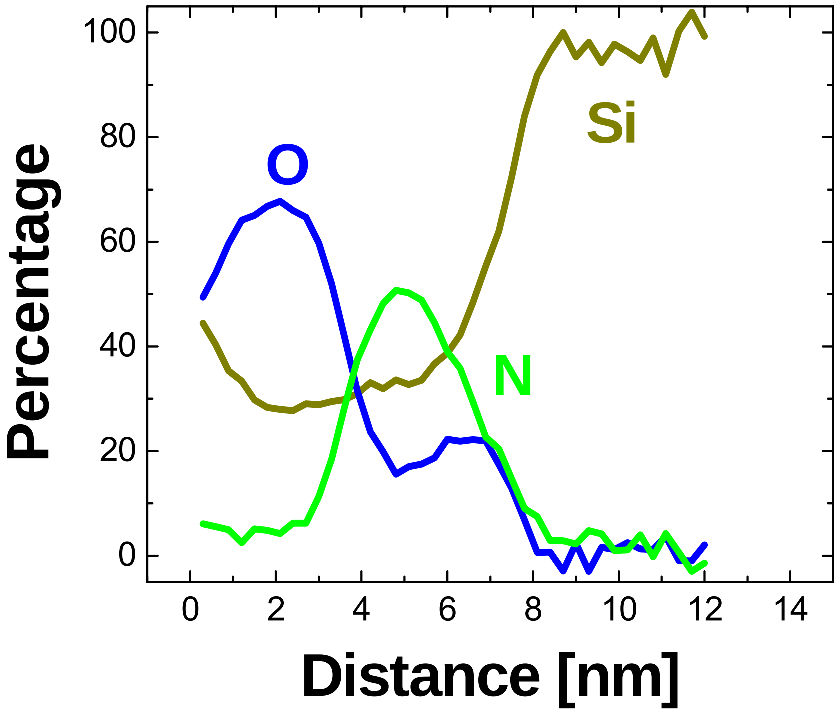
N peak shifted towards poly Si

Two different Si-O-N gate dielectrics

Comparison to AES depth profiling

Test layer stack: SiO_2/Si-O-N/Si



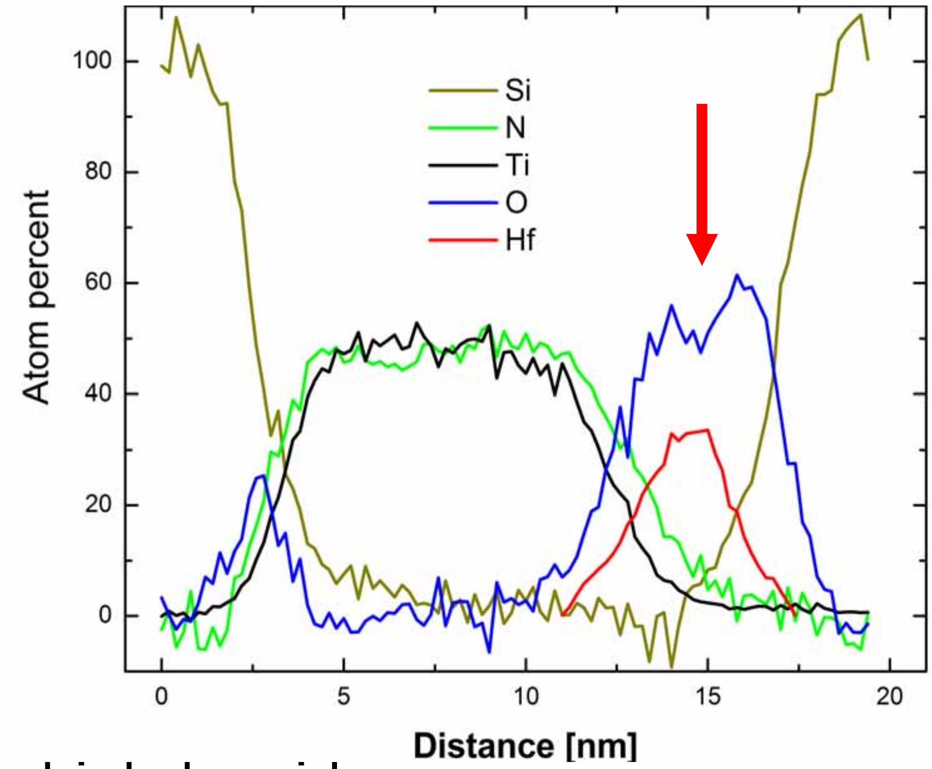


Auger Electron Spectroscopic (AES) depth profiles

EELS linescans of the same layer stack
→ slightly better depth resolution (about 0.5 nm)

Quantitative EELS of high-κ metal oxide dielectrics

TiN/poly Si-capped
Hf-O-Si gate
electrode stack



- O concentration dip in the high-k oxide

→ O depletion or artifact due to strong elastic scattering in the Hf-rich layer ?

- EELS quantification is problematic in the presence of strongly scattering components

→ Correction factors may have to be applied!

Quantitative EELS of low-κ intermetal dielectrics

Carbon depletion in low-κ IMDs

- Substitution of oxygen in SiO_2 by methyl groups (-CH3) reduces the permittivity significantly ($\kappa = 4.0 \rightarrow 2.6\text{-}3.3$)

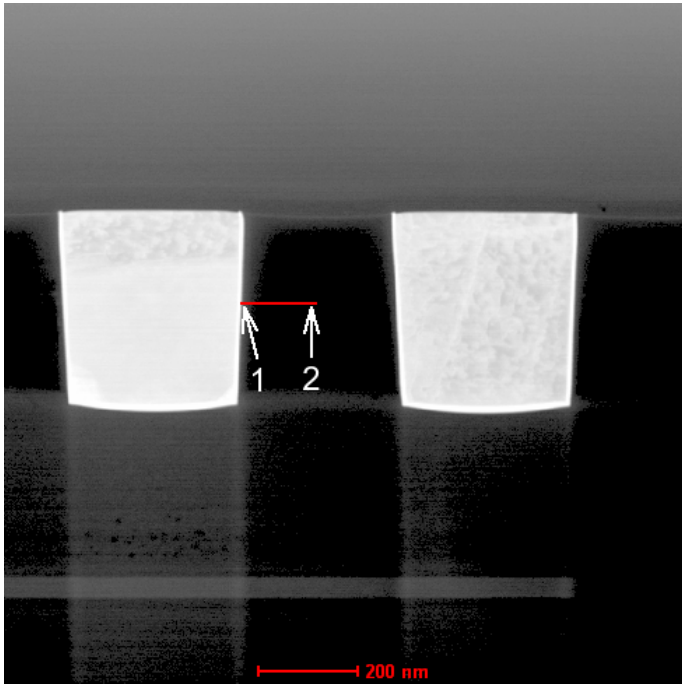
→ Carbon doped intermetal dielectric materials (IMD) reduce interconnect delay, power dissipation, and crosstalk noise

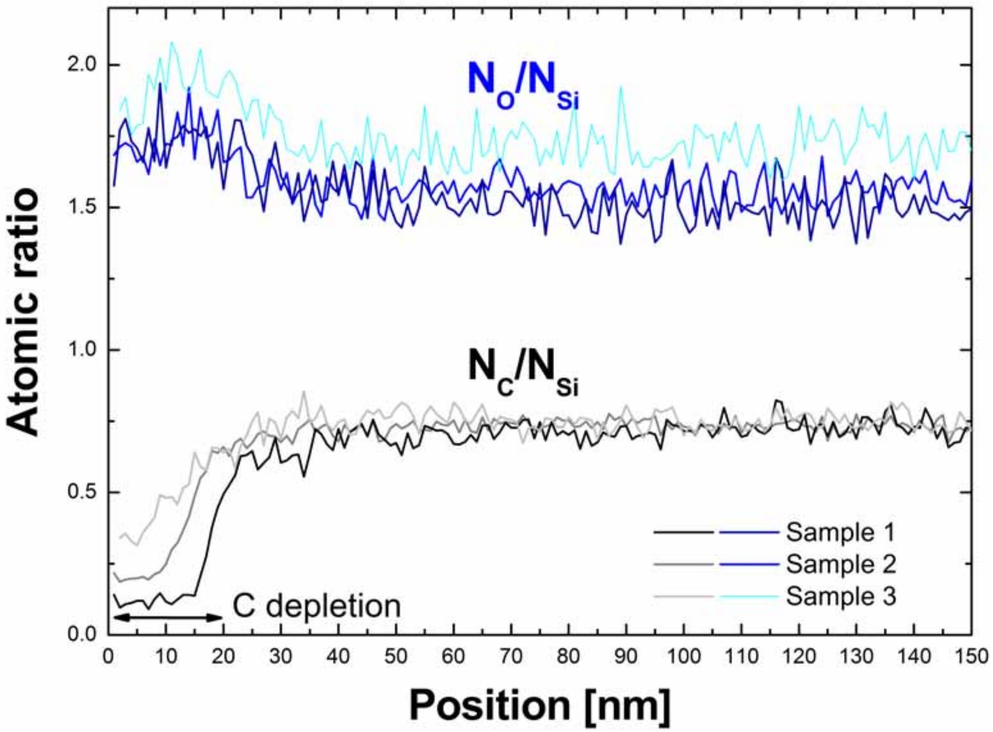
- Plasma processing for resist stripping, trench etching and post-etch cleaning removes molecular groups that contain C and H from the near-surface layer (10-20 nm)

→ Increased water absorption and dimensional changes

→ Quantitative EELS analysis of structured IMD films with nanometer resolution for process optimization

EELS line scans across carbon depletion zones





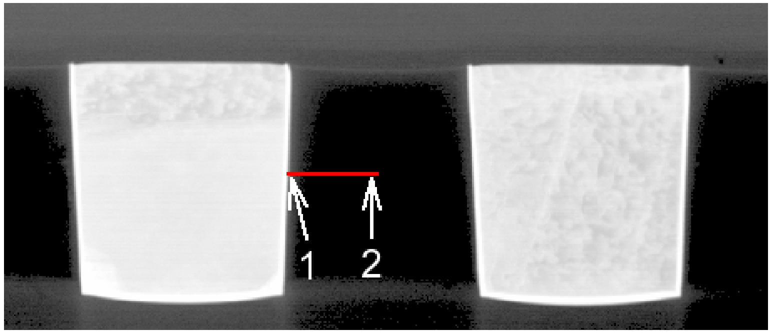
Cu interconnect lines embedded in SiCOH (HAADF-STEM image)

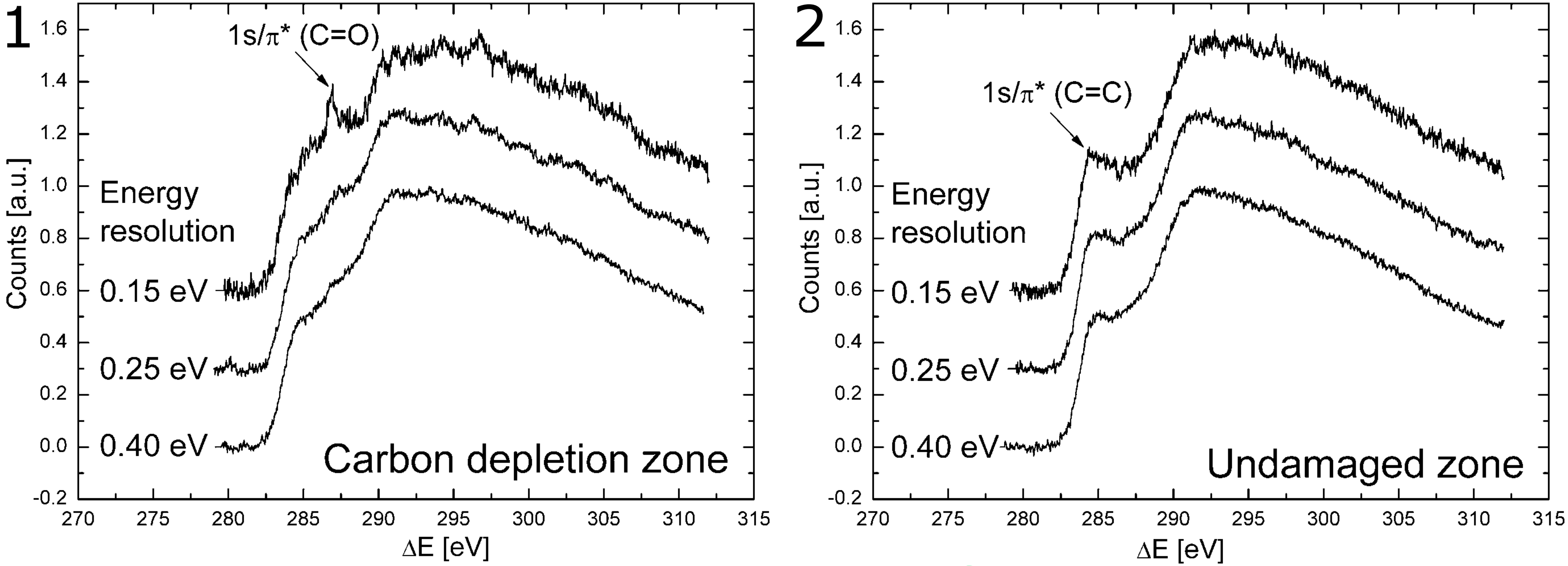
Atomic ratios calculated from EELS line scans

ELNES analysis of low-κ intermetal dielectrics and nickel silicides

Energy loss near-edge structure (ELNES) analysis of low-κ IMD

ELNES of the C-K edge at three different FEG monochromator settings
→ three different energy resolutions





Carbon depletion zone shows modified bonding

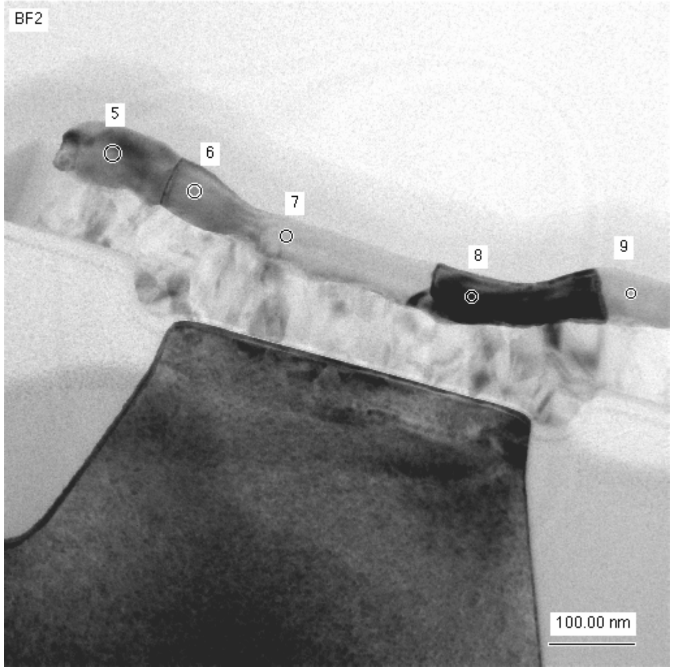
→ Investigate process induced low-κ dielectric modification and damage mechanisms

Metal silicide phase identification

- The formation properties of self-aligning metal silicides on narrow lines depend on process temperatures, dopant concentrations, and line width
- The introduction of nickel mono-silicide (NiSi) requires a thorough investigation of these effects and their relation to process parameters

→ **Identify silicide phases with nanometer resolution for process optimization**

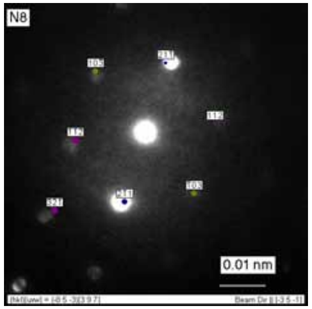
Metal silicide phase identification by electron microdiffraction



Results often ambiguous due to strong crystal orientation dependence of the diffraction patterns

NiSi

$NiSi_2$



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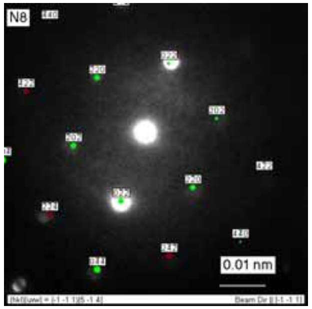

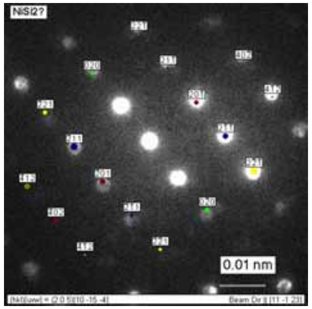

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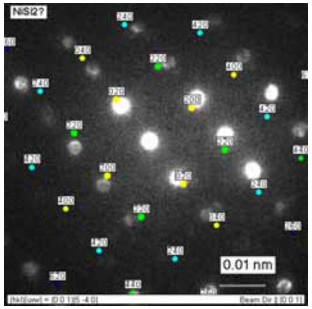

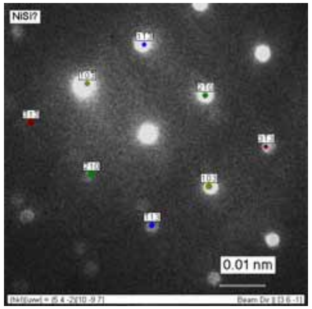

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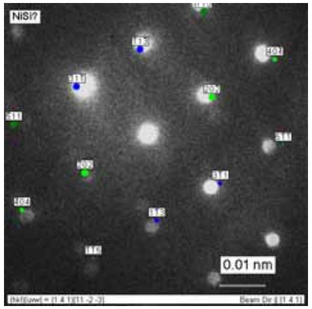
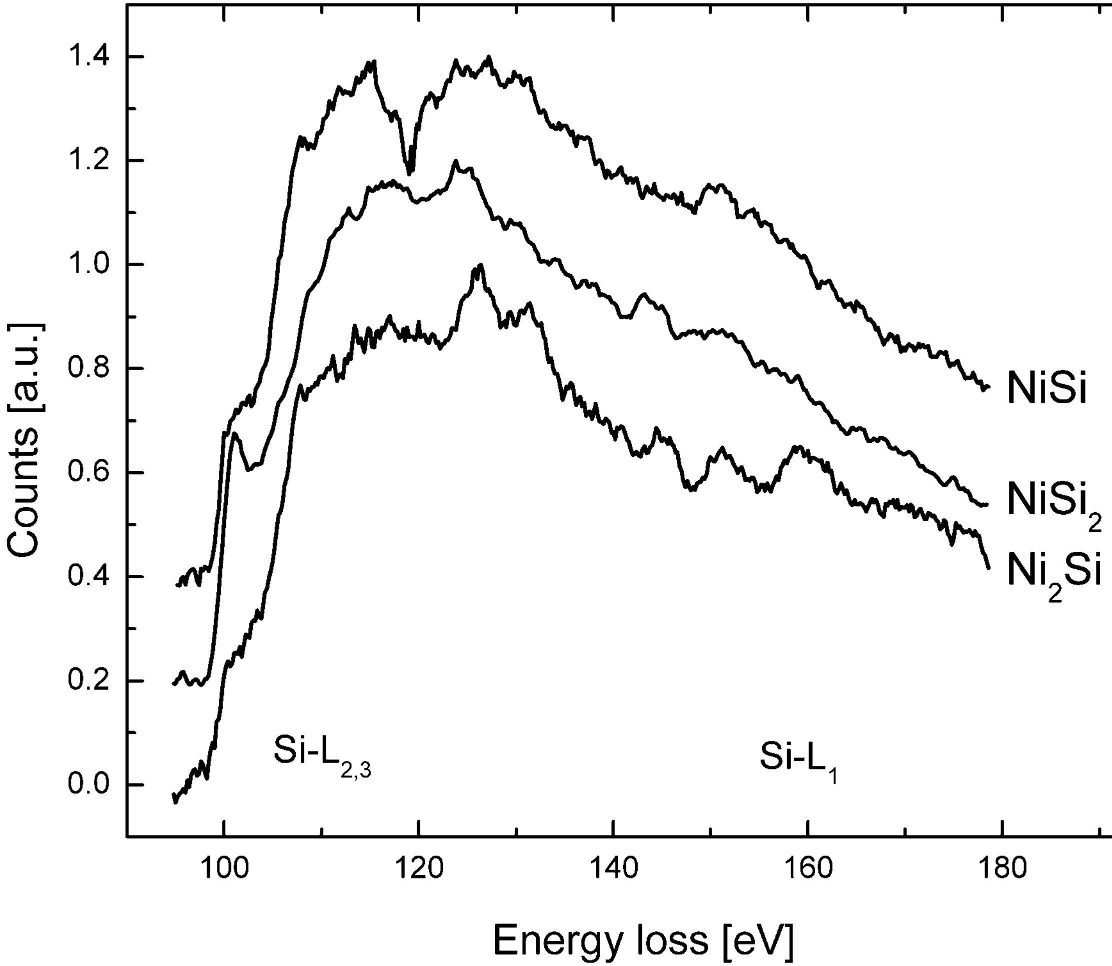


Metal silicide phase identification by ELNES of the Si-$L_{2,3}$ edge



Si-$L_{2,3}$ ELNES of NiSi, $NiSi_2$, and Ni_2Si (energy resolution 1 eV)

→ Each phase shows a distinct fine structure that can be used for phase identification (‘ELNES fingerprinting’)

Summary

Advanced TEM-EELS techniques provide valuable high spatial resolution information for process development:

- Accurate compositional analysis using Image-EELS
- Quantitative N, O, Si, C, … concentration profiling by means of reference spectra fitting of EELS linescans
- Chemical bonding analysis of low-κ dielectric materials using ELNES analysis
- Phase identification of metal silicides by ELNES fingerprinting