Definition of Contrast

\[
\text{contrast} \equiv \frac{\Delta I}{I}
\]
Example: Cellulose + CdSe NPs
Mass-Thickness Contrast

- Primary contrast mechanism for amorphous materials
- Incoherent, elastic scattering
- Enhance by: 1) staining, 2) smaller objective aperture

\[ I(T) = I_0 e^{-\mu T} \]

\[ \mu = \frac{N_0 \cdot \rho \cdot \sigma_0}{A} \]

\[ \mu T = \left( \frac{N_0 \sigma_0}{A} \right) \cdot (\rho T) \]

\( \rho T \): mass-thickness (g/cm\(^2\))
Theorem of reciprocity

STEM image contrast is related to TEM image contrast

\[ \alpha_{\text{TEM}} \leftrightarrow \beta_{\text{STEM}} \]
\[ \beta_{\text{TEM}} \leftrightarrow \alpha_{\text{STEM}} \]
**STEM BF/ADF**

• No significant post-specimen focusing in STEM

• Eliminates post-specimen chromatic aberration

• Bright-field and annular dark-field detectors

• Photomultipliers or solid-state detectors

BF STEM of 10-nm Au
Retractable STEM detector

BF ADF

incident beam
def lens 1
def lens 2
condenser lens
Bragg reflections

Z contrast diffraction contrast
Diffraction Contrast

• Nearly always contributes to images of crystalline materials
• Coherent, elastic scattering

Useful to image:
• Dislocations/defects
• Chemical interfaces
• Structural phases

For crystalline materials, always show the direction of \( \mathbf{g} \)
STEM in an SEM

STEM Image of Recrystallized Si

Acquired in an SEM (with STEM detector)!
Z-contrast imaging

• Uses a high-angle annular dark-field (HAADF) detector
• Incoherent, elastic scattering
• Eliminates diffraction contrast
• Enhances chemical contrast
• Best not to cool sample

\[
\frac{d\sigma}{d\Omega} (\theta) = |f(\theta)|^2
\]

\[
f_e(\theta) = \frac{\lambda^2 Ze^2 m}{8\pi h^2 \varepsilon_0} \left[ \frac{1}{\sin^2(\theta/2) + \sin^2(\theta_0/2)} \right]
\]

\[
f_e(\theta) \propto \frac{Z}{\sin^2(\theta_0/2)} \quad \text{(low angle, screened)}
\]

\[
f_e(\theta) \propto \frac{Z}{\sin^2(\theta/2)} \quad \text{(high angle, unscreened)}
\]
Screening and Atomic Radius

\[ \varphi(r) = \frac{Ze}{4\pi\varepsilon_0 r} e^{-r/r_0} \]  
//Thomas-Fermi model for screened electrostatic potential of atom

\[ 4\pi \sin(\theta_0/2) = \frac{\lambda}{r_0} \]  
\[ \lambda \ll r_0 \quad \longrightarrow \quad \theta_0 \approx \frac{\lambda}{2\pi r_0} \]

\[ r_0 \approx \frac{a_B}{Z^{1/3}} \]  
//Wentzel atom model

\[ \theta_0 \propto Z^{1/3} \quad \longrightarrow \quad f_e(\theta) \propto Z^{1/3} \]  
(low angle, screened)

HAADF examples

InAs Synthesized with Au Catalysts

Conventional BF

Inverted Contrast

HAADF

No diffraction contrast

GaAs/GaPAs QD superlattice

"HAADF"

GaAs