Overview of Phase Contrast & High resolution TEM

Lecture 14
High-resolution EM

*general idea*

Incident electron wave

Sample (very thin!)

Transmitted & diffracted waves

Transmitted & diffracted waves each have a different phase

Result is an interference pattern - our ‘phase contrast’ or HREM image
High-resolution EM

general idea

Image courtesy U. Dahmen, NCEM, LBNL
High-resolution EM

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Why are the phases different?

Transmitted & diffracted waves are allowed wave functions in the crystal

- Together they form the “Exit Wave” which leaves the crystal

They solve Schrödinger’s Equation

\[ \nabla^2 \psi \left(\mathbf{r}\right) + \frac{8\pi m e}{\hbar^2} \left[ E + V(\mathbf{r}) \right] \psi \left(\mathbf{r}\right) = 0 \]

Solutions are Bloch Waves:

\[ b^{(j)} \left( k^{(j)}, \mathbf{r} \right) = \sum_g C^{(j)}_g \exp \left[ 2\pi i \left( k^{(j)} + g \mathbf{g} \right) \cdot \mathbf{r} \right] \]

Amplitude term  Phase term
High-resolution EM

**general idea**

Looking at these Bloch waves:

\[
b^{(j)}(\vec{r}) = \sum_{g} C_{g}^{(j)} \exp \left[ 2\pi i \left( k^{(j)} + g \right) \vec{r} \right]
\]

Phase term has to do with the strength & spacing of the periodic potential of the lattice along a given direction in the crystal \((g)\).

Different diffracted waves have different phase shifts.

The total "Exit Wave" is thus the sum over all of the Bloch waves:

\[
\psi_{\text{total}} = \sum_{j=1}^{n} A^{(j)} \psi^{(j)} = \sum_{j=1}^{n} A^{(j)} b(k^{(j)}, \vec{r})
\]
High-resolution EM

general idea

Image courtesy U. Dahmen, NCEM, LBNL
High-resolution EM

*general idea*

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Incident electron wave

Sample (very thin!)

Transmitted & Diffracted waves

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So, appears “simple” enough …

(1) Calculate the phase differences for the different diffracted waves

(2) Create an interference pattern from the overlap of these phases in two-dimensions
High-resolution EM

**general idea**

Not even this “simple”

The TEM has very poor lenses

- Spherical aberration in particular

This aberration causes diffracted waves to be ‘phase shifted’ by the objective lens

- Complex dependence on wavelength, $C_s$, diffraction vector and defocus
- Magnitude of shift varies with distance from optic axis
  - And thus diffraction angle
  - Thus each diffracted wave undergoes a different phase shift

Complicates image interpretation
High-resolution EM

*general idea*

Returning to this picture

This means that the phases of the diffracted waves are changed by the objective lens focus
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Spherical aberration
**High-resolution EM**

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So, appears “simple” enough …

1. **Calculate the phase differences for the different diffracted waves**

2. **Create an interference pattern from the overlap of these phases in two-dimensions**
High-resolution EM

**general idea**

Thus, the image you get STRONGLY DEPENDS ON THE FOCUS CONDITION

A single HREM image

The ‘unscrambled’ exit wave

Image courtesy C. Kisielowski, NCEM, LBNL

Simulation: Si $N_{1,2}$

0.18 nm