Transmission electron microscope (wikipedia)

EM Pixel Array Detector (EMPAD)

High speed, high dynamic range

$\text{Si}_3\text{N}_4$

Projected potential

Simulation - 9 nm defocus

Simulation - 3 nm defocus

$\Sigma_q \Sigma_q' <q|T(q',q)|q'> <q'\Omega(z,0)|x'> <q\Omega(z,0)|x'>$

Fourier Synthesis

Transfer

Fourier Transform

$|x'> \Omega(z,0)|x'>$
Elastic Scattering: \[ \nabla^2 \Psi(\vec{r}) + \left[ E + V(\vec{r}) \right] \Psi(\vec{r}) = 0 \]

incident energy \[ \uparrow \] electrostatic potential

2+1 dimensions: \[ \Psi(\vec{p}, z) = e^{ik_z z} \Psi(\vec{p}, z) \]

\[ i k_z \frac{\partial}{\partial z} \Psi(\vec{p}, z) = -\left[ \nabla^2 + (k_z - E) + V(\vec{p},z) + \frac{\partial^2}{\partial z^2} \right] \Psi(\vec{p}, z) \]

\[ \leftarrow\text{Schrödinger-like equation} \]

"unitary evolution" \[ i \frac{\partial}{\partial z} U(z,0) = H(\vec{p},z) \ U(z,0) \]

"Multislice" \[ U(z_n,0) = U(z_n,z_{n-1}) \cdots U(z_1,0) \]

\[ \leftarrow\uparrow\leftarrow\rightarrow\]

\[ U(z''',z') \approx e^{-\int_{z''}^{z'} H(\vec{p},z) \ dz} \]

4-D STEM Ptychography

Ptycho = "fold" (Greek)

Scan sample and merge 4-D dataset \( (x,y,k_x,k_y) \)

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**Figure 1. Measuring complex polarization textures with EMPAD.** (A) Schematic of electron microscopy pixel array detector (EMPAD) placed in the diffraction plane, where a convergent beam electron diffraction (CBED) pattern is formed at the detector. Polarity causes an asymmetry in intensities of the conjugated pairs of diffracted disks at \(-G\) and \(-G\), where \( G \) is the reciprocal lattice vector, indicated as light and dark gray disks. We utilize this aspect of the electron scattering distribution by taking the probability current flow, (B) \( (p_2) \) of [200] and (C) \( (p_2) \) of [020] diffracted disks, in units of inverse Angstrom, to reconstruct polarization vortices in (D). Scale bar in B-D represent a length of 2 nm.
**Measuring electric polarization**

Beam momentum: $\langle \mathbf{p} \rangle = \langle \Psi | \frac{\hbar}{i} \mathbf{\nabla} | \Psi \rangle$

Ehrenfest: $\frac{d}{dt} \langle \mathbf{p} \rangle = \langle [\mathbf{H}, \mathbf{p}] \rangle = q \left( \mathbf{E} + \frac{1}{c} \mathbf{v} \times \mathbf{B} \right)$

Integrate through sample: $\mathbf{p} = \int dt \dot{\mathbf{p}} = \frac{q}{\sqrt{2}} \int dz \mathbf{E}$

**Magnetic polarization** Lorentz microscopy