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PhD Cornell 2018 (Chemical physics)

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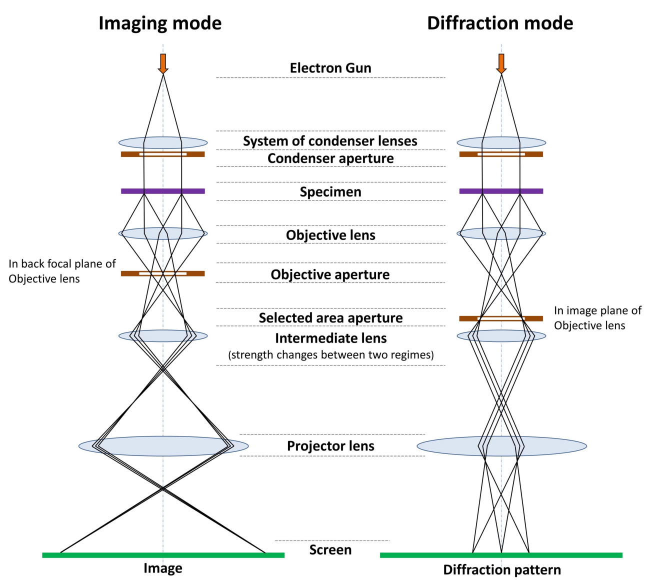
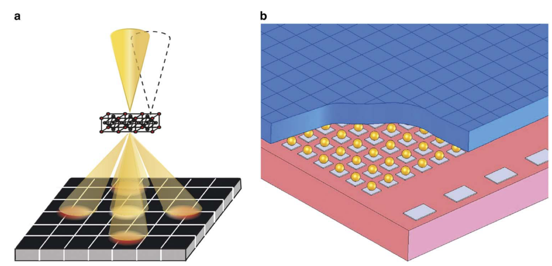
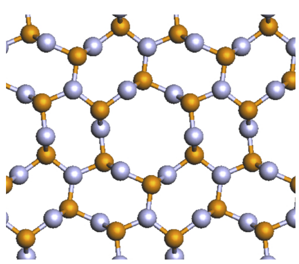
Transmission electron microscope (wikipedia)



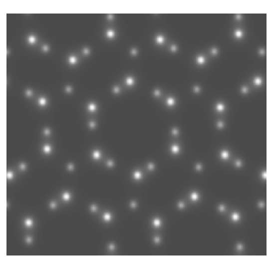
EM Pixel Array Detector (EMPAD)



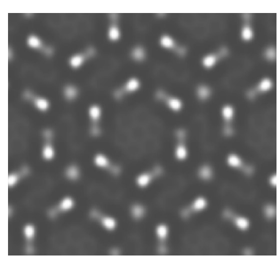
High speed, high dynamic range



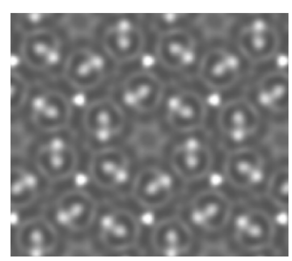
Si_3N_4



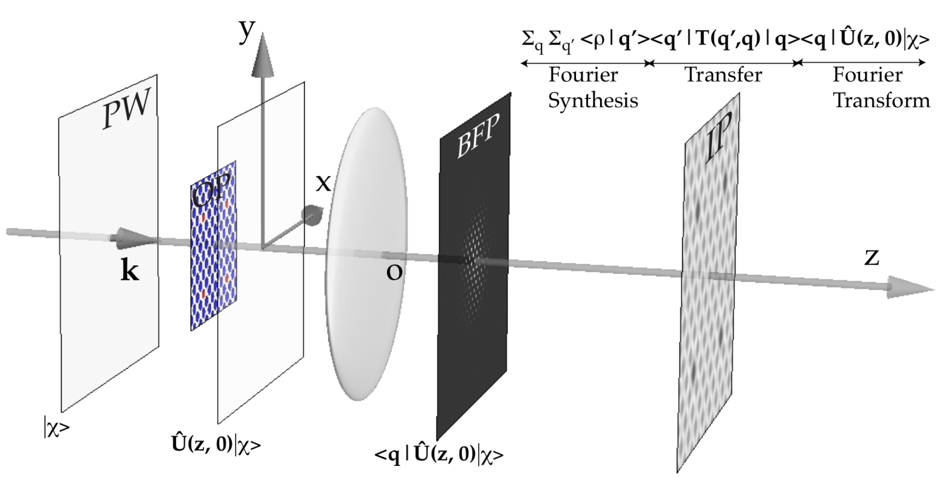
projected potential



Simulation -9 nm defocus



Simulation -3 nm defocus



Elastic Scattering: $\nabla^2\psi(\vec{r}) + [E + V(\vec{r})]\psi(\vec{r}) = 0$

(E ← incident energy; $V(\vec{r})$ ← electrostatic potential)

2+1 dimensions: $\psi(\vec{\rho}, z) = e^{ik_z z}\,\Psi(\vec{\rho}, z)$

$$ik_z \frac{\partial}{\partial z}\Psi(\vec{\rho}, z) = -\left[\nabla^2_{\vec{\rho}} + (k_z^2 - E) + V(\vec{\rho}, z) + \cancel{\frac{\partial^2}{\partial z^2}}\right]\Psi(\vec{\rho}, z)$$

neglect backscattering

↑ Schrödinger-like equation

"Unitary evolution" $i\frac{\partial}{\partial z}U(z,0) = H(\vec{\rho}, z)\,U(z,0)$

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

$$U(z'', z') \approx e^{-\int_{z'}^{z''} H(\vec{\rho}, z)\,dz}$$

4-D STEM Ptychography

Ptycho = "fold" (Greek)

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

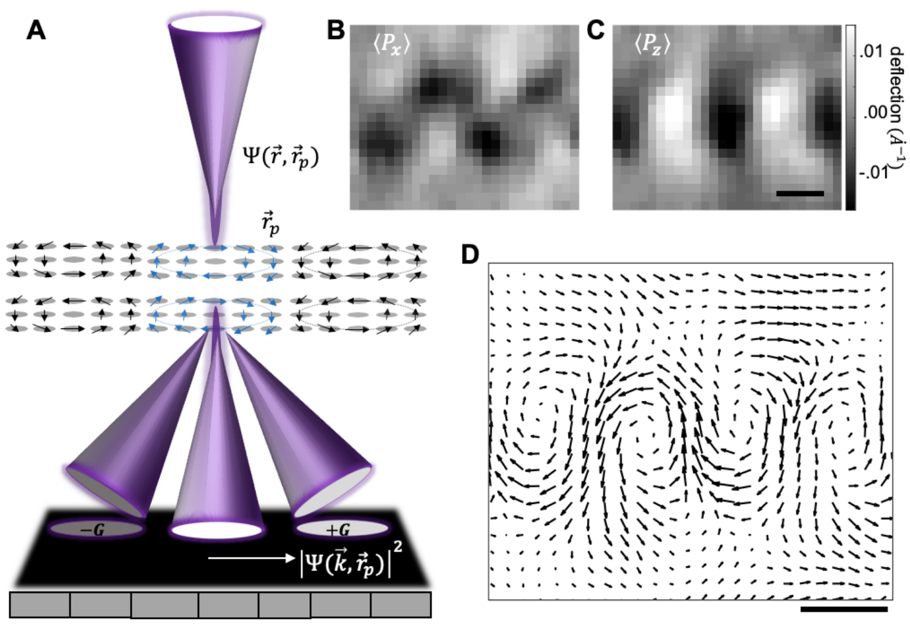


Figure 1. **Measuring complex polarization textures with EMPAD.** (**A**) Schematic of electron microscopy pixel array detector (EMPAD) placed in the diffraction plane, where a convergent beam electron diffraction (CBED) pattern is formed at the detector. Polarity causes an asymmetry in intensities of 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**) $\langle P_x \rangle$ of [200] and (**C**) $\langle P_z \rangle$ 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: $\langle \vec{p} \rangle = \langle \psi | \frac{\hbar}{i} \vec{\nabla} | \psi \rangle$

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

Integrate through sample: $\vec{p} = \int dt \, \dot{\vec{p}} = \frac{q}{v_z} \int dz \, \vec{E}$

Magnetic polarization   Lorentz microscopy