Aberration Correction in Microscopes

Weishi Wan
ALS/Accelerator Physics Group, LBNL

TEAM 0.5 Results

Atomic Resolution Imaging with a Sub-50-pm Electron Probe

Erni et al, PRL 102, 096101 (2009)

Graphene at the Edge: Stability and Dynamics

Girit et al, Science 323, 1705 (2009)
The TEAM Project

TEAM: Transmission Electron Aberration-Corrected Microscope

- **Genesis of TEAM**
  - Lawrence Berkeley National Laboratory, Argonne National Laboratory, Brookhaven National Laboratory, Oak Ridge National Laboratory, University of Illinois, Urbana-Champaign
- **Project begins**
  - Start stage development
  - Lawrence Berkeley National Laboratory
  - Oak Ridge National Laboratory
  - Argonne National Laboratory
- **Start probe corrector development**
  - Lawrence Berkeley National Laboratory
- **Start $C_C$ corrector development**
  - Argonne National Laboratory
- **Installation of TEAM 0.5 at NCEM, Lawrence Berkeley National Laboratory**
- **TEAM 0.5 begins user Operations at NCEM**
- **TEAM I begins Facility operations at NCEM**

Timeline:

- 00
- 04
- 05
- 06
- 07
- 08
- 09
- 10

- DOE approves mission need
- $C_C$ corrector
- Design review
- $C_C$ DDCOR prototype demonstrated
- 0.5Å $C_C$ corrected STEM demonstrated
- 0.5Å $C_C$ corrected TEM demonstrated
- $C_C$ corrected prototype demonstrated
- 0.5Å $C_S + C_C$ corrected STEM/TEM demonstrated
- Prototype TEAM stage complete
- 0.5Å CS + CC corrected STEM/TEM achieved
Electron Microscopes: Basics

- Transmission electron microscope (TEM)
- Scanning transmission electron microscope (STEM)
- Photoemission electron microscope (PEEM)
- Low energy electron microscope (LEEM)
- Scanning Electron Microscope (SEM)

Krivanek et al, UltraMicrosc 78, 1 (1999)
Philips CM200, NCEM LBNL
PEEM2, ALS LBNL
Electron Microscopes: Optics

- Round lenses: fewest allowed aberrations
- Magnetic lenses: > 100 kV
- Electrostatic lenses: < 50 kV
- Round lenses are always focusing

Most important aberrations:

Spherical: $\Delta r = C_s \alpha^3$
Chromatic: $\Delta r = C_c \alpha \Delta E/E$

Scherzer’ theorem: $C_s < 0, C_c > 0$

(Scherzer, Z. Phys. 101, 593 (1936))
Aberration Reduction vs Correction

Aberration reduction:

• Lenses optimization: 30s-80s, done
• Resolution for TEM/STEM: 1Å
• Resolution for LEEM: 4 nm
• Resolution for PEEM: 20 nm

Aberration correction:

• Possibility #1: multipoles
• Possibility #2: mirror
• Known for decades
• Became feasible in the past decade

A Simple Multipole Corrector


Cc Corrector for SEM

Cs Corrector for STEM
Krivanek et al, UltraMicrosc 78, 1 (1999)
$C_s$ ($C_3/C_5$) Corrector for STEM

**Cs/Cc Corrector for TEM**


- Center magnets: electrostatic and magnetic dodecapoles
- One more octupole to correct the cross term
- First-order Wien filter to correct $C_c$
- Voltage stability: $< 4e^{-8}$!
- Current stability: $< 1.5e^{-8}$!
Stability Demonstrated!

$\Delta I/I = 8.1 \times 10^{-9}$

$\Delta V/V = 3.6 \times 10^{-9}$

TEAM $C_c$ Corrector: First Test

Blue circle: 1Å

Elemental map of La:
- a) uncorrected; b) corrected

How Does an Electron Mirror Work?

Round lens

Electron mirror
Aberration Correction for PEEM/LEEM

- Rotational symmetry
- Large field of view


courtesy of J. Feng
New Challenge: Beam Separator

SMART at BESSY II

Target resolution: 1 nm

Simplifying the Beam Separator

- Single pass dispersive
- Separate elements
- Simple magnet
- Conventional lenses

Wan et al, NIMA 564, 537 (2006)
PEEM3 at ALS

Target resolution: 4 nm
Simplified aberration-corrected + energy-filtered LEEM

Use existing, simple prism array design
Single electrostatic lens couples prisms
Maintains straight column layout
Symmetry cancels dispersion, all 2nd order aberrations, as well as chr. ab. of magnification
Integrated energy filter without additional optics

< 1.5 nm in LEEM
< 4 nm in PEEM (>10 eV)

courtesy of R. Trump
First results: everything works as expected.

- PEEM 80 µm
- LEEM dirty Si 2.7 µm
- LEED dirty Si

Note dispersion of secondary electrons after 2nd pass through prism: restores energy filter function

courtesy of R. Trump
Summary

• Aberration correction in electron microscopes has become a reality
• Technological advancement over the past decade has been phenomenal
• Great science is being done using these devices and much is coming