Materials Science 460: Electron Microscopy

Northwestern University, McCormick School of Engineering

Winter Quarter 2024

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Course Philosophy

This course embraces McCormick's "whole-brain engineering" approach by combining rigorous analytical methods with creative problem-solving. Students will develop both convergent thinking (through quantitative analysis and theoretical understanding) and divergent thinking (through experimental design and data interpretation) in electron microscopy.

Course Description

This course provides a comprehensive introduction to electron microscopy with an emphasis on transmission electron microscopy (TEM) and its applications in materials science. Through a combination of theoretical understanding and hands-on experience, students will develop both analytical and intuitive approaches to microscopy.

Learning Objectives

By the end of this course, students will be able to:

1. Master the fundamental principles of electron microscopy
2. Operate TEM instruments with proper technique and safety awareness
3. Analyze and interpret diffraction patterns and imaging data
4. Perform quantitative analysis using EDS and EELS
5. Apply advanced TEM techniques to materials characterization
6. Develop creative approaches to solving materials characterization challenges

Course Information

Meeting Times:

- Lectures: Monday & Wednesday, 11:00 AM - 12:20 PM
- Office Hours: Friday, 11:00 AM - 12:20 PM
- Laboratory Sessions: Alternate Weeks (Schedule TBD)

Course Materials

Recommended Text

Williams, D.B., & Carter, C.B. (2009). *Transmission Electron Microscopy: A Textbook for Materials Science* (2nd ed.). Springer New York. DOI: `https://doi.org/10.1007/978-0-387-76501-3`

While this textbook is not mandatory, it serves as an excellent reference and comprehensive guide. The text consists of four integrated volumes covering different aspects of TEM. Northwestern University library provides access to the electronic version through SpringerLink.

Additional Reference Texts

1. Egerton, R.F. (2016). *Physical Principles of Electron Microscopy: An Introduction to TEM, SEM, and AEM* (2nd ed.). Springer International Publishing. DOI:`https://doi.org/10.1007/978-3-319-39877-8`
2. De Graef, M. (2003). *Introduction to Conventional Transmission Electron Microscopy.* Cambridge University Press. ISBN: 978-0-521-62995-9
3. Fultz, B., & Howe, J. (2012). *Transmission Electron Microscopy and Diffractometry of Materials.* Graduate Texts in Physics. Springer Berlin Heidelberg. ISBN: 978-3-642-(available through SpringerLink)

Additional Resources

- **Course Materials:**
  - Lecture notes and slides (Canvas)
  - Laboratory protocols and guides
  - Problem sets and solutions
- **Research Articles:** Curated collection of recent publications demonstrating advanced TEM applications.
- **Online Resources: (Available on Canvas)**
  - Online lecture modules
  - Microscopy databases and simulation tools

Software and Computing Resources

- **Microscopy Software:**
  - Digital micrograph (available on Gatan's website or NU*ANCE* workstations)
- **Data Analysis:**
  - Python-based exercises will be provided through Canvas
  - Basic packages (NumPy, matplotlib, scikit-image)
  - Example scripts and tutorials available for common TEM analyses
  - **No prior programming experience required!**

Note: All necessary software packages are available on the computers of the NU*ANCE* facility. Students will receive guided instruction on data analysis methods throughout the course.

Course Schedule & Assignments

Codes used in this class will be posted in NU-MSE-LECTURES/460-WINTER2025

Week 1: Introduction to Electron Microscopy and Materials Characterization

Monday:

- Course Introduction
- Microscopy in materials science research
- Length scales and resolution limits
- Comparison of characterization techniques

Wednesday:

- Information from electron microscopy
- Structure-property relationships
- Case studies in materials research
- Introduction to microscope components

Homework 1: Analysis of research papers using TEM and comparison of characterization techniques

Week 2: Physical Principles of Electron Microscopy

Monday:

- Wave-particle duality
- De Broglie wavelength
- Electron-matter interactions overview

- Basic contrast mechanisms

Wednesday:

- Elastic and inelastic scattering
- Energy transfer processes
- Interaction volume concepts
- Introduction to diffraction principles

Lab 1: Safety & Basic Operation

- Safety protocols and emergency procedures
- Microscope startup and shutdown
- Basic alignment exercises
- Vacuum system operation

Homework 2: Electron wavelength calculations and interaction cross sections

Week 3: Foundations of Electron Diffraction

Monday:

- Crystal structure review
- Real and reciprocal space relationships
- Geometric theory of diffraction
- Introduction to the Ewald sphere

Wednesday:

- Bragg's law in electron diffraction
- Formation of diffraction patterns
- Relationship between real and reciprocal space
- Practical aspects of diffraction experiments

Homework 3: Crystal structure analysis and reciprocal space calculations

Week 4: Diffraction Analysis and Applications

Monday:

- Selected Area Electron Diffraction (SAED)
- Calibration procedures
- Zone axis patterns
- Kikuchi lines and bands

Wednesday:

- Convergent Beam Electron Diffraction (CBED)
- Space group determination
- Orientation relationships
- Phase identification

Lab 2: Diffraction Techniques

- SAED pattern acquisition and analysis
- Camera length calibration
- Zone axis alignment
- Basic crystallography measurements

Homework 4: Diffraction pattern indexing and analysis

Week 5: Imaging Fundamentals

Monday:

- Bright field imaging
- Dark field imaging
- Mass-thickness contrast
- Diffraction contrast basics

Wednesday:

- Two-beam conditions
- Systematic row excitations
- Thickness fringes
- Bend contours

Homework 5: Image contrast analysis and interpretation

Week 6: Defect Analysis

Monday:

- Dislocation contrast theory
- Burgers vector determination
- Stacking fault analysis
- Strain field imaging

Wednesday:

- Grain boundaries
- Interface analysis
- Precipitate characterization
- Defect density measurements

Lab 3: Imaging Defect Analysis

- Bright/dark field imaging
- Two-beam condition setup
- Defect characterization
- Image acquisition optimization

Homework 6: Defect characterization problems

Week 7: High-Resolution TEM

Monday:

- Phase contrast imaging
- Resolution limits
- Lens aberrations
- Image formation theory

Wednesday:

- Sample preparation for HRTEM
- Through-focus series
- Image simulation concepts
- Interpretation of HRTEM images

Homework 7: HRTEM image analysis

Week 8: Analytical TEM

Monday:

- EDS principles
- X-ray generation and detection
- Quantitative analysis
- Spatial resolution in EDS

Wednesday:

- EELS fundamentals
- Fine structure analysis
- Chemical mapping
- Thickness measurements

Lab 4: Analytical Methods

- EDS data collection
- EELS acquisition
- Quantitative analysis
- Chemical mapping

Homework 8: Spectroscopy data analysis

Week 9: Advanced Techniques

Monday:

- Intro to scanning transmission electron microscopy (STEM)
- Z-contrast imaging
- Aberration correction
- In-situ TEM

Wednesday:

- 4D-STEM
- Energy-filtered TEM
- Electron holography
- Environmental TEM

Homework 9: Advanced methods analysis

Week 10: Special Topics and Future Directions

Monday:

- Cryo-EM techniques
- Machine learning in TEM
- Big data in microscopy
- Recent developments

Wednesday:

- Final project presentations
- Course review
- Future perspectives
- Career opportunities in microscopy

Important Dates:

- January 6: First day of classes
- January 20: No classes (Martin Luther King Jr. Day)
- February 14: Last day to drop a class
- March 15: End of Winter Classes

Course Deadlines:

- All homework assignments are due by 11:59 PM on the due date
- Lab reports are due two weeks after each lab session
- Lab sessions will be held in the NU*ANCE* facility (AB Wing)
- Final presentations will be held during regular class time on March 12

Presentation Format:

- 10-minute oral presentation
- 5-minute Q&A session
- Conference-style presentation format
- Professional slide deck required

Session Guidelines:

- Presentations will be organized into thematic sessions
- Strict time keeping will be enforced

- Professional conference etiquette expected
- Attendance for all presentations is mandatory

Presentation Requirements:

- Clear statement of research question/objective
- Concise methodology description
- Key results and findings
- Main conclusions and impact
- High-quality figures and graphics
- Proper acknowledgments

Evaluation Criteria:

- Technical content and depth (40%)
- Presentation clarity and organization (30%)
- Visual quality of slides (15%)
- Handling of questions (15%)

Professional Development Note: This conference-style presentation serves as a valuable experience for future scientific conferences and professional meetings. Students are encouraged to treat this as an opportunity to develop their scientific communication skills.

Assessment

- Weekly Homework Assignments (9 total): 40%
- Laboratory Reports (4 total): 30%
- Final Project: 30%

Laboratory Sessions (4 Total)

1. **Safety & Basic Operation** (Week 2)
2. **Diffraction Techniques** (Week 4)
3. **Imaging & Defect Analysis** (Week 6)
4. **Analytical Methods** (Week 8)

Whole-Brain Approach

This course integrates analytical and creative thinking through:

- Quantitative analysis of electron-matter interactions
- Creative problem-solving in experimental design
- Intuitive understanding of image formation
- Systematic approach to data interpretation
- Innovative applications to real materials problems

Academic Integrity

Students are expected to comply with Northwestern University's Academic Integrity Policy.

- Original work on all assignments
- Proper citation of sources
- Individual completion of homework (unless specified as group work)
- Accurate reporting of laboratory data
- Ethical data analysis and presentation

This course follows the Northwestern University Syllabus Standards. Students are responsible for familiarizing themselves with this information.