EMA6518: Transmission Electron Microscopy
Fall 2017
3 Credits
Prerequisites: EMA 3513C or equivalent
Classroom location: CSE E122
Meeting times: MWF period 5 (11:45 a.m. – 12:35 p.m.)

I. Instructor information

Dr. Nicholas G. Rudawski
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Office hours: by appointment only (please do not come to my office unannounced)
Class website: run through e-learning at elearning.ufl.edu

II. Course description and objectives

This course provides an introduction and overview of transmission electron microscopy (TEM) as emphasized for materials scientists and those studying the physical sciences with emphasis placed mainly on analysis of inorganic materials (metals, semiconductors, and ceramics). This course also will provide students with the theoretical background required for operation of the TEMs at the Research Service Centers (RSC). By the end of the course, students will be able to understand the following:

Basics of microscopy and lenses
Basic construction and modes of operation of a TEM
TEM instrumentation
Typical TEM sample preparation methods
Basics of electron scattering
Electron diffraction patterns
Amplitude contrast in TEM images
Fault analysis using TEM
Phase contrast in images
High-resolution imaging
Scanning TEM
Use of TEM for chemical analysis

III. Recommended textbooks

1. "Transmission electron microscopy: a textbook for materials science" by Williams and Carter; second edition (ISBN: 978-0-387-76500-6)

   http://link.springer.com/book/10.1007/978-0-387-76501-3/page/1

2. "Transmission electron microscopy and diffractometry of materials" by Fultz and Howe; third edition (ISBN: 978-3-540-73885-5)

   http://link.springer.com/book/10.1007/978-3-540-73886-2/page/1

Both of these textbooks are available online, fully downloadable, and completely free of charge at the above respective links when accessed through the UF network. Additionally, print black and white hardcopies may be ordered for $25 through the same links when accessed through the UF network; if you are planning on doing a lot of TEM work, I strongly recommend you invest in hardcopies of these books as both are excellent TEM reference texts, particularly for materials scientists or those studying the physical sciences.

IV. Course outline

A. Tentative course schedule and suggested reading (subject to change)

Date	Topic(s)	Recommended reading
08/21	Introduction; microscopy basics; electrons for microscopy; TEM history, advantages/disadvantages, basic electron-sample interactions	WC: 1 (entire)
08/23	Ray diagrams; lens basics (resolution, focusing, angles, depth of field/focus)	WC: 6.1, 6.2, 6.7; FH: 2.2
08/25	Magnetic lenses; lens defects; spherical/chromatic aberration, astigmatism; objective lens; TEM resolution, knock-on damage, C_s correction	WC: 4.6.E, 6.3 – 6.6; FH: 2.7.1. – 2.7.4
08/28	TEM environment; basic TEM construction; TEM illumination system (gun, C1/C2 lenses), gun types, illumination modes	WC: 5.1 – 5.4, 8.1, 9.1 – 9.1C; FH: 2.4.1, 2.4.2
08/30	TEM image forming system; imaging/diffraction modes; non-lens TEM components; cameras and screens; camera dynamic range; holders	WC: 9.1D, 9.2 – 9.3A, 7.2, 7.3C
09/01	TEM sample preparation; TEM grids; polishing; etching; ion milling; FIB; XTEM versus PTEM	WC: 10 (entire)
09/06	Electron scattering basics; wavefunctions; scattering from a single atom; cross-sections; atomic scattering factor	WC: 2.1 – 2.6, 3.1 – 3.8; FH: 3.1
09/08	Scattering from many atoms; light diffraction patterns; Bragg's law; TEM diffraction patterns; camera equation	WC: 2.8 – 2.12, 3.10B, 9.6.B, 11.3

		– 11.6; FH: 5.1
09/11	TEM imaging modes for single-crystal, polycrystalline, and amorphous specimens	WC: 9.3A – 9.3C; FH: 2.3
09/13	Open Q&A for exam 1; crystallography basics (planes, directions, lattice/basis); hexagonal crystal system	TBD
09/15	**EXAM 1** (08/21 – 09/11)	N/A
09/18	d-spacing; reciprocal lattice; structure factor	WC: 3.9, 12.1 – 12.3; FH: 5.2
09/20	Reciprocal lattice; structure factor calculations for different crystals	WC: 12.1 – 12.3, 16.1 – 16.7, 16.9; FH: 5.3.2
09/22	Reciprocal lattice; structure factor calculations for different crystals	WC: 12.1 – 12.3, 16.1 – 16.7, 16.9; FH: 5.3.2
09/25	Shape factor; Weiss zone axis law; Ewald sphere	WC: 12.5 – 12.7, 17.1, 17.2; FH: 5.4
09/27	Ewald sphere; reciprocal lattice-DP relationship; deviation parameter	WC: 12.5 – 12.7; FH: 5.6 – 5.8
09/29	Indexing of single-crystal DPs	WC: 18.1- 18.4, 18.10; FH: 6.1
10/02	Indexing of single-crystal DPs	WC: 18.1- 18.4, 18.10; FH: 6.1
10/04	Indexing of single-crystal DPs	WC: 18.1- 18.4, 18.10; FH: 6.1
10/09	Indexing polycrystalline DPs; DPs from low-symmetry crystals; tilt influence on DPs; double diffraction; Kikuchi diffraction; SingleCrystal DP simulation software	WC: 18.9, 19 (entire); FH: 6.3, 6.4
10/11	Open Q&A for Exam 2; image-DP relationship; orientation relationships; calculating deviation parameter; convergent beam electron diffraction	WC: 18.11, 19 (entire); FH: 6.3
10/13	**EXAM 2** (09/13 – 10/09)	N/A
10/16	Concept of contrast; contrast mechanisms; amplitude contrast; mass-thickness contrast; 2-beam condition; diffraction contrast in perfect single crystals	WC: 22.1 – 22.3.B, 22.3.D, 22.3.E, 22.5, 24.1 – 24.4; FH: 7.1 – 7.2.4, 7.5, 7.6
10/18	Diffraction contrast in polycrystalline samples; defective single crystals; dislocations; stacking faults; Burgers vector determination	WC: 25.5, 26.1 – 26.6; FH: 7.7, 7.8
10/20	Contrast sharpness; weak-beam dark-field; fault vector determination; contrast from two-dimensional defects (stacking faults)	WC: 22.5, 26.1 – 26.6; FH: 7.10 – 7.12
10/23	Bragg beam approach to dynamical scattering; crystal potential; extinction distance; Howie-Whelan equations	WC: 13 (entire)
10/25	Dynamical scattering and Bloch wave formalism; Bethe equations; thickness fringes revisited	WC: 14 (entire)

10/27	High-resolution TEM; phase contrast; origins of lattice fringes; objective aperture size;	WC: 23.1 – 23.4
10/30	Interpreting HR-TEM images; extraneous lattice fringes; role of TEM; convolutions and Fourier transforms	WC: 23.4, 28.1 – 28.8, 28.10; FH: 10.4 – 10.5
11/01	Role of defocus, spherical aberration, phase shift error; contrast transfer function; intensity transfer function	WC: 28.1 – 28.8; FH: 10.3.1 – 10.3.3
11/03	Optimizing the intensity transfer function; Scherzer conditions; role of specimen quality; orientation, thickness, and defocus effects	WC: 28.1 – 28.8; FH: 10.3.1 – 10.3.3, 10.5.3
11/06	Open Q&A for Exam 3; image filtering; measuring C_s and defocus; Moire fringes; STEM basics	WC: 9.4, 23.5, 23.6, 31.1 – 31.5B
11/08	**EXAM 3** (10/11 – 11/03)	N/A
11/13	STEM modes; STEM detectors; detector dynamic range; spot size and semi-angle of convergence	WC: 7.3.A, 7.3.B, 9.4.B; FH: 11.1 – 11.5
11/15	STEM probe optimization; orientation and thickness effects in HAADF-STEM images;	TBD
11/17	STEM applications; comparing HAADF-STEM to HR-TEM; C_s-corrected STEM; intro to analytical TEM	TBD
11/20	Analytical TEM; generation of characteristic X-rays; Fluorescence yield; EDS systems; TEM settings; EDS artifacts	WC: 4.2, 32 (entire), 36.1, 36.2, 36.4 (intro only); FH: 4.6
11/27	Mode of performing EDS; qualitative and quantitative EDS	WC: 34 (entire), 35 (entire); FH: 4.6.4
11/29	EELS basics; band theory of solids; EELS instrumentation; features of EELS spectra	WC: 37.1 – 37.4, 39.1 – 39.3, 40.1 – 40.4; FH: 4.2, 4.3
12/01	Modes of performing EELS; STEM SI and EFTEM SI; qualitative and quantitative EELS	WC: 37.6, 37.8, 38.2, 39.4; FH: 4.4, 4.5
12/04	Open Q&A for Exam 4; time allotted to cover any remaining material	TBD
12/06	**EXAM 4** (11/06 – 12/04)	N/A

B. Putting theory into practice: live TEM demos

It is beneficial for all of you to observe some live demonstrations of TEM principles discussed in class so as to start to put theory into practice and gain some basic practical familiarity with TEM. The demos will be prerecorded and uploaded to the course website, allowing you to watch said demos at your convenience. Watching of the demos is completely optional and is not intended as a means to enhance your ability to succeed in this course but rather as an enhancement to the course in general.

C. Recommended reading

Recommended reading from both textbooks for each class is specified in the above tentative schedule (subject to change). All the information you will need to complete this course will be covered in the lectures and thus performing the recommended reading is optional. It remains unclear if there is any correlation/causation between performing the recommended reading and performance in this course, but performing the recommended reading certainly will not hinder your ability to succeed in this course (and there isn't any financial barrier since you can access the books for free, too).

D. List of assessments

1. Four (4) in-class exams (20% of final score for each exam)

   The exams will be 15 questions and multiple-choice format; this is to remove the ambiguity and fairness issues that tend to accompany the grading of essay/extended answer questions.

   Tentative exam dates: 09/15, 10/13, 11/08, and 12/06

2. Weekly (approximately) homework assignments (20% of final score)

   The weekly homework assignments will be essay/extended answer in nature and will also include old exam questions to help you better prepare for the actual exams. However unlike the exams, the grading of the homework assignments will be pass/fail and on the basis of "effort", rather than correctness; in other words, if you make a reasonable effort on a homework assignment (including justifying your answers and/or showing your work where relevant), you will receive a grade of "pass" for it. You may work together in groups on the homework assignments, but each student must turn in his or her own homework. Your homework assignments may be typed and/or handwritten, either is acceptable. However, each homework assignment must be turned in through the course website as a single document in PDF format by the assigned deadlines and must be complete; a "complete" homework assignment is one that has **all** parts completed. Homework not turned in through the course website (e.g. emailed directly to me) and/or not in PDF format and/or not completed will be graded as "fail". To remain fair to all students, I cannot make exceptions for computer malfunctions, Internet outages, incomplete/blank

uploads, or any other mistakes (honest or otherwise). I strongly suggest you download and view your assignment after you upload it to make sure everything is in order; you will be allowed an unlimited number of resubmissions prior to each homework deadline to make sure everything is in order.

3. Four (4) out-of class extra credit mini-projects (optional)

   These will be essay/extended answer in nature and will usually be mathematical and/or computational in nature. These will also be graded on the basis of *correctness* as well as effort (i.e. justifying your answers and/or showing your work where relevant). Attempting of the mini-projects is completely optional. You may work together in groups on the mini-projects, but each student must turn in his or her own mini-project and you are expected to complete the mini-project without any assistance from me. The turning in of mini-projects follows the exact same stipulations and conditions outlined for the turning in of homework. Grading of the mini-projects will be "all or nothing" in nature. In other words, you will either receive full credit for the mini-project or you will receive no credit. To receive full credit on a mini-project, all parts must be completed correctly and you must show your work. Successful completion of a mini-project will result in the addition of 1 bonus point on a subsequent exam, and thus provides you with the opportunity to improve your exam score by ~6.7%.

4. Four (4) in-class, unannounced extra credit quizzes (optional)

   The quizzes will be 10 questions and true/false format; again, this is for reasons similar to those outlined regarding the exams. The first quiz will be given between the drop/add deadline and the first exam, the second quiz between the first and second exams, the third quiz between the second and third exams, and the fourth quiz between the third and fourth exams. The unannounced quizzes will start promptly at the beginning of class; if you arrive more than 5 min late, you will not be allowed to take the quiz. The quizzes provide an opportunity to earn bonus credit on the exams and to give you an incentive to attend class and keep up with the material. Scoring 6 or fewer, 7, 8, 9, and 10 correct questions will result in 0, 0.75, 1.0, 1.25, and 1.5 bonus points, respectively, to be added on to each subsequent exam. Thus, each bonus quiz provides the opportunity to improve an exam score by up to 10%. If you are an EDGE student, you will also have the opportunity to take these quizzes, which will be proctored in the same manner as the exams (but obviously will not be subject to any attendance requirements).

E. Make-up assessments policy

In general, make-ups for missed exams or extensions for late homework will not be given except in cases of illness, planned attendance of academic-related functions (research conferences, etc.), family emergencies, or genuinely extenuating circumstance. If you claim you could not be present to take an exam due to an aforementioned reason, you may take the exam at a later date subject to verification of your need to be absent. You have until 5:00 PM on the last day of the drop/add period (08/25) to inform me of any planned absences due to academic-related functions so that I may accommodate you accordingly. Absences for reasons not previously mentioned (e.g., missing class to go on vacation, oversleeping, etc.), will not be accommodated. No make-ups will be given for missed extra credit quizzes or mini-projects for **any** reason.

V. TEM training

Those of you who intend to use the FEI Tecnai F20 S/TEM as part of your research may start training a few weeks into the course (or anytime after the course is completed). You must apply for an RSC account (https://rsc.aux.eng.ufl.edu/) and set up a funding source before starting training (if you haven't already done this, I suggest you start now to avoid any potential delays). Graduate research assistants who intend to use the TEMs regularly for research purposes while at UF may apply for training. Coursework only students, students who are interested in getting trained for purposes of resume padding, or students who do not have a regular need to use the instrument as part of their research projects are not eligible.

VI. Class emails

A group email list will be used to send out as-needed mass communications for purposes of sudden schedule changes (which hopefully will not happen), clarification of course material, and/or other important issues.

VII. Attendance and classroom conduct

Attendance is not required, and based on my experience over the past several years I am forced to begrudgingly conclude that regular attendance may not even be necessary to perform well in this or any course. However, you will have to attend class regularly if you want to take advantage of the extra credit opportunity via the unannounced quizzes and you must be present to take the exams. If you choose to attend class, please be respectful and pay attention; silence/put away your cell phones; please do not bring and read newspapers; you may bring in your laptop computers to take digital notes, but please do not use your computers for leisurely activities (aimlessly surfing the internet, accessing social media sites, playing games, etc.). As the instructor, I reserve the right to have anyone removed from the classroom that is acting disrespectfully and/or disruptively.

VIII. Grading procedure

An absolute grading scale will be used for this course as follows:

90% ≤ A
90% > A- ≥ 87%
87% > B+ ≥ 84%
84% > B ≥ 80%
80% > B- ≥ 77%
77% > C+ ≥ 74%
74% > C ≥ 70% (lowest possible passing grade)

This scale is based on grade data collected over the last five years of teaching this course. Greater information on current UF policies for assigning grade points can be found at: http://gradcatalog.ufl.edu/. Your final grade will be rounded to the nearest whole percent (e.g. 89.51% will get rounded up to 90% and 69.49% will get rounded down to 69%).

IX. Concerns about grades

I have made every effort to be as transparent as I possibly can be about grading so there are no surprises and you all know exactly how well you need to do to obtain certain grades. You will also have access to old exams and old bonus quizzes from past years to help you prepare. Furthermore, the optional extra credit opportunities also have the potential to improve each exam score by up to ~16.7%. If you have specific concerns about course material, I am more than happy to discuss these with you. However, I am not willing to meet with you if you are simply unhappy about your grade and want to express your frustration with me, want me to provide you with special grading leniency, or want me to provide you with a special extra credit opportunity to improve your grade. The *only* provided extra credit opportunities will be those already outlined in this syllabus; I suggest that you take as much advantage of those opportunities as you possibly can.

X. Performing well in this course

The people who perform well in this course are those who are able to properly and correctly understand the material and (at minimum) also complete the homework assignments. As far as understanding the material is concerned, some students may be able to do this at a very high level with very little effort besides attending class and/or watching the video lectures (and basically never attending class except for taking the exams). Other students may attend class regularly, take detailed notes, re-watch the video lectures, read the textbooks, go through the old exams, and regularly ask lots of questions (in other words, put in a tremendous amount of effort) and will still have difficultly understanding the material at a mediocre level. I cannot guarantee that you will receive a good grade simply by putting a lot of effort into this course; ultimately, it comes down to performance. That being said, my experience over several years of

teaching is that the students who perform well tend to be those who put in more effort; however, I'm not necessary sure that there is a causal relationship between effort and understanding of the material; it may be the case that students who have an easier time understanding the material become more interested in the material and therefore are more driven to put in effort (so it may be like a positive feedback loop).

XI. Academic misconduct

Academic misconduct (cheating, plagiarism, comparing exam answers after the conclusion of an exam, etc.) is a very serious matter and will not be tolerated in any capacity; all students are required to abide by the Student Honor Code as described in detail at:

https://www.dso.ufl.edu/sccr/process/student-conduct-honor-code/

It is the responsibility of you, the students, to understand what does and does not constitute a violation of the student honor code. If I believe any student is violating the student honor code, it will be reported immediately to academic services in the MSE department, fully investigated, and (if necessary) properly sanctioned.

XII. Accommodations for students with disabilities

Students requesting classroom accommodation must first register with the Dean of Students Office. The Dean of Students Office will provide documentation to the student who must then provide this documentation to the instructor when requesting accommodation.