Analytical Transmission Electron Microscopy for Sustainable Materials, 6hp

1. Course name and size

Analytical Transmission Electron Microscopy for Sustainable Materials, 6 ECTS

2. Course organization

The course is a joint activity within Swedish Research Infrastructure for Advanced Electron Microscopy (ARTEMI) and lead by Stockholm University. All six universities in ARTEMI, also WISE-universities, are involved in the course.

Course nodes

All course developers from different WISE universities (ARTEMI nodes) are professors with extensive competence in organizing and lecturing at courses in TEM at both masters and PhD-level.

- prof. Gunnar Svensson, dr. Tom Willhammar, Stockholm University
- prof. Per Persson, Linköping University
- prof. Reine Wallenberg, prof. Kimberly Dick Thelander, Lund University
- prof. Eva Olsson, Chalmers University of Technology
- prof. Klaus Leifer, Uppsala University
- prof Jonas Weissenrieder, prof Peter Hedström, KTH - Royal Institute of Technology

3. Course description including intended learning outcome

In the development of new sustainable materials it is essential to obtain a facile understanding of their nature. Transmission electron microscopy provides essential tools to obtain knowledge about the structures of materials across five orders of magnitude down to the atomic scale as well as providing understanding for their chemical and physical properties. The course will provide an introduction to analytical transmission electron microscopy as applied to materials science, with case-specific applications in the development of sustainable materials. It covers the experimental techniques of transmission electron microscopy (TEM) and scanning transmission electron microscopy (STEM). The course will provide an overview description of available electron microscope instrumentation and the fundamental physics of image formation. Various techniques for structural analysis available in the TEM will be presented such as TEM/STEM imaging, electron diffraction and the practical knowledge necessary to perform these methods and interpret the results will be introduced. The course also provides a succinct overview of two widely-used spectroscopy techniques - energy dispersive X-ray spectroscopy (EDS) and electron energy loss spectroscopy (EELS) - emphasizing how they can be used to obtain information about the chemical composition (EDS and EELS) and electronic structure (EELS) on length scales ranging from micrometers down to the atomic level. The course will strongly emphasize how TEM can be applied in the development of sustainable materials and will focus on the practical utilization of the techniques in materials science. In addition, important aspects such as sample preparation techniques and in-situ experiments will be covered. The theoretical part will be examined with a written assignment.

Each participant will experience two full day practical sessions at two different ARTEMI nodes. Each of these will be based on the study of a sustainable material or research question to illustrate how TEM can support when solving a scientific question in this field. The students will be given the opportunity to indicate which two practical exercises they are most interested in, although we will distribute them evenly over the nodes. The practical session will start with providing a background of the sustainable material(s) of interest. The practical session should end in a short report and an oral presentation.

As a part of the course, the student should write a project proposal to ARTEMI on how TEM can be used in their PhD projects or in a tentative study if not relevant. The proposals should be written in such a way that they can be submitted to ARTEMI to potentially result in an initiated new project.

4. Course plan

Prerequisites and other conditions for access to the course

The students are expected to have a masters degree in natural science, engineering or equivalent.

Course content

The course covers how analytical transmission electron microscope techniques can contribute to research for a sustainable society.

The course will provide an overview description of the analytical transmission electron microscope instrumentation and the basic physics of image formation and associated spectroscopical methods. It will also give in depth examples of studies on materials important for the development towards a sustainable society where analytical transmission electron microscopy is crucial.

The course also includes two full days of practical exercises, being case studies on two different ARTEMI nodes on materials relevant for sustainability studied at those sites.

Learning goals

After completing the course the students are expected to:

- Have a good knowledge in how a transmission electron microscopes and associated detectors and spectrometers work, their possibilities and limitations.
- Have an understanding of how transmission electron microscopy can contribute to research on materials important for the transformation to a sustainable society.
- Be able to write an ARTEMI application for TEM studies.

Education

The education consists of lectures both on-site and via video link, hands-on exercises on microscopes, demonstrations, group exercises and group work.

Examination

The course is examined in the following way: a written assignment, writing short reports and oral presentations from the on-site practical sessions, and writing an application for TEM studies to ARTEMI infrastructure.

Tentative schedule

Lectures 1-5 will be on site in Stockholm during a lunch-to-lunch event; September 11-12, kl 13:00 to 12:15.
Lectures 6-12 will be remote via Zoom kl 10-12; 16/9, 17/9, 18/9, 23/9, 24/9 (two 1 h lectures), 25/9

Lecture	Suggested Lecture Topic	Responsible ARTEMI node
1*	*ARTEMI* – possibilities, inspiration presentation of the research on materials for a sustainable development where TEM is important at the different nodes.	SU, LiU, LU, CTH, UU, KTH
2*	*Introduction to transmission electron microscopy (TEM) and the various techniques available.* The lecture will provide an overview of the instrumentation, electron-optics and electron matter interaction as well as recent advancements such as the aberration correction	SU
3*	*TEM imaging: BF, DF and phase contrast* Imaging in the TEM will be described with focus on practical utilization if the technique. High resolution transmission electron microscopy (HRTEM) will be	SU

	covered. Examples from materials with sustainable aspects will be highlighted.	
4*	*Sample preparation for TEM studies.* Sample preparation is essential to obtain good data. The most used tchniques will be covered such as powders, focus ion beam (FIB), ion milling, ultramicrotome, cryo-transfer	SU
5*	*Electron diffraction enables highly sensitive and high-throughput phase analysis and atomic structure determination*. Fundamental aspects of electron diffraction, unit cell and crystal symmetry will be covered in order to provide a fundamental understanding of the relationship between real and reciprocal space. New three-dimensional electron diffraction (3D ED) techniques will be introduced for characterization of e.g. nanoporous materials that are important for catalysis, gas separation and capture of pollutants.	SU
6	*Scanning transmission electron microscopy (STEM) as an important technique to study sustainable materials.* Image formation using STEM will be described as well as different imaging modes and their application to sustainable materials such as low-dmensional structures and engineered bulk materials.	LiU
7	*Using TEM/SEM/FIB for studies of soft matter.* Soft matter and hybride materials are sensistive for beam damage and the lecture will among others address how to avoid this.	Chalmers
8	*Spectroscopy reveals the chemical nature of energy materials.* Energy dispersive X-ray spectroscopy (EDS) and Electron energy loss spectroscopy (EELS) will be described and how they can be used to study chemical and physical features down to atomic scale.	UU
9	*In-situ HRTEM, electron diffraction and high resolution compositional analysis applied to semiconductor nanowires.* In-situ TEM can be used to follow the growth of a material, such as a semiconductor proding insights to how the conditions creates changes in crystal structure and formation of defects.	LU
10	*Time resolved TEM opens the window to understand ultra-fast dynamics in materials.* Ultrafast diffuse scattering of nonequilibrium phonon dynamics and its relevance to thermoelectric materials. Magnetization dynamics	KTH
11	*Complementary use of SEM, TEM and APT (atomic probe tomography) for sustainable metals.* Microscopy of nanoscale particles precipitating in the solid-state and which are crucial for the properties of high-performance metallic materials	KTH
12	*How to write an application to ARTEMI***	LiU

* *Lectures on site at Stockholm University*
** *The teachers and researchers in ARTEMI will be available for consulting to find a suitable subject.*

Practical sessions

The practical sessions, on selected materials relevant for sustainable research, are on site. Each session is 7h with approximately four students in each group. Each student will visit two nodes, as far as possible in accordance with their preferences. At the visits also local facilities for TEM sample preparation will be shown and discussed.

Node	Practical sessions	Planned dates
SU	Electron crystallography -high-throughput phase analysis and atomic structure determination of nanoporous adsorbents/catalysts for removal of pollutants	22-23 oct
LiU	STEM studies of 2D-MAXene materials for energy storage, electromagnetic shielding, and filtration. Imaging and spectroscopy at atomic resolution.	5-6 nov
LU	Production of biofuel for aircraft. In-situ TEM studies of deoxygenation of wood based biofuel with NiMo nanoparticles.	5-6 nov
Chalmers	TEM studies of semiconductor nanowires for solar cell applications. The laboratory includes in-situ, imaging and spectroscopy	12-13 nov
UU	TEM to analyze materials from battery research and magnetic materials. A) Solar cell materials as kesterite $Cu_2ZnSnS(Se)$. B) EELS based EMCD for understanding magnetism and to support the development of novel magnetic materials.	22-23 oct
KTH	Ultrafast Electron Microscopy and Spectroscopy - Photon-Induced Near-field Electron Microscopy (PINEM) on thermoelectrics	12-13 nov

5. Number of participants

The practical exercises limits the number of participants to 6*4 = 24. The lectures are open for all.