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Current status and future directions for *in situ* transmission electron microscopy

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Abstract

This review article discusses the current and future possibilities for the application of *in situ* transmission electron microscopy to reveal synthesis pathways and functional mechanisms in complex and nanoscale materials. The findings of a group of scientists, representing academia, government labs and private sector entities (predominantly commercial vendors) during a workshop, held at the Center for Nanoscale Science and Technology- National Institute of Science and Technology (CNST-NIST), are discussed. We provide a comprehensive review of the scientific needs and future instrument and technique developments required to meet them.

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Keywords

In situ TEM; heating holder; indentation holder; liquid/gas cell holder; ETEM; DTEM; direct electron detectors; phase transformation; structure property relationship; gas/liquid-solid interactions

1. Introduction

Over the past decades, the applications of transmission electron microscopy (TEM) have shifted from *post mortem* characterization to live or *in situ* measurements of structure, chemistry and properties of nanomaterials. The speed of this paradigm shift has recently accelerated due to adoption of novel technologies, such as aberration correction and micro-electro-mechanical system (MEMS) device integration. The motivation for *in situ* TEM is to meet the scientific challenges such as elucidating synthesis routes, determining chemical activity of nanoparticles, nanoscale property measurement, and atomic scale failure mechanisms, leading to the establishment of more productive synthesis/fabrication-structure-property relationships (Figure 1a). Research interest in this area is reflected in (a) an exponential growth in number of publications over last 3 years (Figure 1b),[1] (b) the fact that each major materials related conference has at least one session related to *in situ* TEM, (c) an increase in the number of workshops on this subject organized by academia and funding agencies. This topic was also covered in a recent workshop organized by Department of Energy-Basic Energy Sciences (DOE-BES) on “Future of Electron Scattering and Diffraction”.[2] Although there have been several other workshops held with the general theme of *in situ* TEM related techniques that covered current science enabled by recent technical developments during 2013 and thereafter, the motivation of the workshop at NIST was to go beyond current capabilities. Here we discuss the scientific questions, identified by the workshop participants, that cannot be addressed by instrumentation the currently available, and what future advancements direction are needed to address them to further the of growth of the field.

For successful *in situ* measurements we need a base instrument, transmission electron microscope/scanning transmission electron microscope (TEM/STEM), which combines high spatial and spectral resolution, and can be interfaced with peripheral equipment for *in situ* experiments. Peripherals include, but are not limited to, sample holders capable of applying external stimuli such as straining, heating, cooling, electrical biasing, reactive environments (liquid or gas reaction cells), and photons. In addition, there is need for data acquisition and processing systems that can improve temporal resolution and are capable of handling the large data sets generated. The proposed improvements in instrumentation, as identified by international group of participants representing viewpoints from academia, government labs and equipment manufacturers, may create large amounts of imaging and spectroscopic data which require high data acquisition and transfer rates. Extracting scientific knowledge from this amount of data can only be done efficiently with proper data mining and evaluation procedures.

1. CURRENT STATUS

It is imperative to review both the available instrumentation and their capabilities/ applications before discussing the future development ideas. Currently a number of modified instruments are available, either commercially or custom designed by research groups (Figure 1a). In the following section we review the three instrumentation areas.

1.1. Specialty Holders

Apart from the heating and cooling, holders with a diverse range of functionalities are now available; examples include, but are not limited to, mechanical, electrical, and optical property measurements.[3–4] The design of *in situ* TEM holders have now progressed to the level that both strength and ductility can be quantified through compression, tension or bending experiments at low (−140 °C) or high (400 °C) temperatures.[5] It is now possible to make high resolution force measurement and control system. These, combined with improve sample geometries lead to new loading mechanisms, and new methods to measure stress and strain locally.[6–8] Figure 2 shows a direct relationship between change in defect density and strength.[9] Mechanical strain has been shown to reduce the dislocation density in single-crystal metals with face centered cubic structure.[6]

Appreciable progress has also been made for the development of windowed cell holders to observe solid/liquid and solid/gas interaction at elevated temperatures.[10–11] Windowed liquid cells have become popular to study the nucleation of nanoparticles from salt solutions, and for electrochemistry, including charging and discharging battery materials (Figure 3).[12–15]

Also, photons as a stimulant for photocatalysis and phase transformations have been used by several groups. Currently, photons are introduced either via a modified sample holder[16–17] or an independent port using optical fiber.[18] A laser source can also be used for local heating and collecting Raman signal through using appropriate spectrometer.[19] The independent port option has an advantage as it can be incorporated in any microscope with minor modifications and does not require a dedicated holder and sample geometry.[18–19]

1.2. Modified TEM Column

1.2.1. Ultra-high vacuum TEM—Ultra-high vacuum TEM is capable of achieving a vacuum level of 10^{-8} Pa in the sample chamber by incorporating extra pumps and is designed to study clean surfaces. Some researchers have fitted the sample chamber of these microscopes with gas leak system to synthesize nanostructures on clean surfaces.[20–21]

1.2.2. Environmental TEM (ETEM)—A TEM with a modified sample area that can accommodate gas pressures up to 2000 Pa without any obstruction of the electron beam or compromising its performance is generally known as environmental TEM. They differ from the gas-cell holders as the gases introduced are not contained by any membrane but fill the entire sample stage region.[23] The total gas flow from the sample region to rest of the column is restricted by sets of apertures placed in the upper and lower polepieces and the region between apertures is pumped using turbo molecular pumps.[24–25] These microscopes are now commercially available and are being extensively used for understanding and measuring gas-

solid interactions at elevated temperatures. Further information can be found in recently published review articles and book chapters.[26–27]

1.2.3. Ultrafast TEM—Conventional *in situ* TEM is limited by the read out frequency of the charge-coupled device (CCD) camera. Direct CCD technology has pushed the limit up to ≈ kHz.[28] Further improvement in time resolution by even faster cameras is possible but will be ultimately (see discussion in 2.1.4) limited by the electron beam current of the electron sources. In recent years the development of time resolved experimental techniques, based on pulsed electron sources which can deliver higher electron currents, has received much attention. There are two methods currently being employed to obtain TEM images with fast time resolution. The first approach, pioneered by Zewail *et al.*, uses a femtosecond laser source synchronized with a laser beam at the sample to achieve high temporal resolution.[29] The key to the method is to keep only a single electron in the column at any one time to reduce space-charge effects. Images are built up from $\approx 10^7$ of these single electron shots that have been precisely correlated with the specimen drive laser. The single electron per pulse method means temporal and spatial resolution can be maintained at the optimum levels, but the fact that the specimen must be pumped $\approx 10^7$ times by the laser means that the process being studied must be perfectly reversible, i.e. the sample must heal between pulses. This means that the highest time and spatial resolution can only be obtained for the study of such reversible effects as molecular interactions, atomic motions, and electronic phase transitions.

The second approach, pioneered by Bostanjoglo and coworkers, aims to generate pulses with enough electrons to form images from a single shot.[30] The single-shot approach means that the process being studied does not need to be perfectly reversible as all the information is obtained from a single specimen drive event. However, the limitation to this method is that space-charge effects in the beam can lead to degradation of resolution, and, even with an optimized microscope source, column, and detector the high current will limit the overall temporal and spatial resolution of the instrument. The key to using this single shot approach is therefore to optimize the components in the microscope to define the space-charge limited resolution of the instrument. This second approach has been developed further at Lawrence Livermore National Laboratory (LLNL) using a modified JEOL 2000FX* for dynamic transmission electron microscopy (DTEM), that now achieves approximately < 5 nm spatial resolution at a time resolution of ≈ 15 ns.[31–34] While all of the existing projects on the LLNL-DTEM are aimed at nanosecond resolution, the microscope itself is capable (with minor modifications) of obtaining *in situ* analysis on timescales from 10^{-6} to 10^{-15} s in single shot (ms to ns) and stroboscopic (ns to fs) modes.[35] The DTEM has been successfully applied to various projects, including crystallization of amorphous semiconducting materials.[31–32, 34, 36–37] Ideally the DTEM platform can be developed to be used in regular TEM mode without the pulsing mode, and it can be easily switched to fast or ultrafast mode.

*DISCLAIMER: Certain commercial equipment, instruments, or materials (or suppliers, or software, etc.) are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose

1.3. Data Collection (Recording media)

While TEM provides an unparalleled platform for atomic scale imaging and spectroscopy for *in situ* observation of dynamic process under external stimuli, its temporal resolution is limited by the data collection or recording media. Most TEM/STEM instruments are equipped with a CCD and/or digital camera. The recording rate for images is dependent on the electron dose, detection quantum efficiency (DQE) of the camera, memory and processer speed of the computer. The Rose criterion for signal to noise ratio (SNR) defines how many electrons are needed for a given resolution, e.g. SNR =5 is needed to achieve 0.2 nm resolution. Therefore, higher frame rate will reduce the SNR and thereby spatial resolution. With a high brightness gun, and using all electrons (DQE =1), we can achieve a frame rate of 1000 s^{-1} as predicted by a back of the envelope calculation. In the last few years, direct detection cameras, capable of high speed (up to a rate of 1600 s^{-1}) have become available.

For imaging in gaseous environment, the situation is further deteriorated due to the coupling of gas ionization to local charge-induced specimen vibration through a capacitive effect. Also at phonon lifetimes of 10 ps, vibration can smear out the electrostatic potential between consecutively delivered electrons.[38] At 50 Pa pressure Si dumbbells can be resolved. Comparable resolution can be achieved under low dose conditions (10^5 e $nm^{-2}s^{-1}$) but at higher pressures: at 1920 Pa the atomic resolution is quite impossible.[38]

Nanomegas* has a lens-coupled system that uses an off-the-shelf system capable of up to a frame rate of 200 s^{-1}, but diffraction pattern collection rate is different; due to precession, the collection rate will be smaller. Recently, direct detection cameras have become commercially available. The higher DQE (0.4 to 0.7) of these cameras makes it possible to reduce image collection time, i.e. recording at frame rates of 40 s^{-1} to 1600 s^{-1} with reasonable SNR.[39–40] Although they have been successfully employed for low dose imaging of biological samples, their applications for *in situ* TEM studies are still in the early stages. [41–42]

2. FUTURE DEVELOPMENT NEEDS

Scientific questions that cannot be addressed using currently available instruments form the basis of future development needs. Results from the discussion groups that included representatives from major manufactures of specimen holders, microscope column and data collection system are given below. It is interesting to note that both academia and vendors have made progress in meeting some of the challenges outlined during the workshop and are included in this section.

Existing challenges can be divided in two broad categories: (a) applicable to all *in situ* experiments (collective challenges) and (b) specific to relevant research field as described below.

2.1. Collective Challenges

2.1.1. Identification/measurement of electron beam effects and their mitigation

—The possibility of constructive or destructive interactions of high energy electron beam with the sample material can be an issue for relating transmission electron microscopy

results with real-life experiments. It becomes especially crucial for understanding chemical reaction mechanisms, where local surface structure and mobility of nanoparticles studied in reactive environments has to be linked to the entire sample in evaluating the process. Not all reactions and/or materials will be affected by electron irradiation. However, the rule of thumb is 'if not proven otherwise, the electron beam affects the samples under observation'. When we observe phenomena in a material using *in situ* TEM and if we intend to correlate the phenomena to the intrinsic characteristics of the material (i.e. those which are not affected by electron irradiation), then it is vital to determine how much of our observation is driven by the electron beam as opposed to the intended stimuli (temperature, gas, stress, etc.). Electron beam effects can be divided in to two broad categories: (1) ionization (that increases with decreasing electron energy); (2) knock-on damage (that increases with increasing electron energy). Damage for materials is expected to be at electron dose rate of 10^5 nm^{-2} s^{-1} to 10^6 nm^{-2} s^{-1} and for biological samples at 10^2 nm^{-2} s^{-1} to 10^{36} nm^{-2} s^{-1}. General procedures to evaluate electron beam effects are difficult to establish as they depend on:

- **a.** Nature of material.
- **b.** Thickness and orientation of the sample with respect to the electron beam.
- **c.** Energy of electrons.
- **d.** Electron current density.
- **e.** Electron dose (=electron current density * irradiation time).
- **f.** Specimen temperature.
- **g.** Vacuum conditions.

As mentioned earlier, it has become more important to understand the electron beam effects as we move away from imaging in vacuum towards gas and liquid environments at various temperatures. Moreover, electron dose becomes an important factor when combining high resolution with high temporal resolution as the resolution of the TEM images is dependent on SNR given by Rose criteria:

$$d_s = \sqrt{d_i^2 + \frac{\left(\frac{S}{N}\right)^2}{C^2 D}}$$

Where d_s is lattice resolution, d_i is the instrumental resolution, S/N is SNR, C is image contrast and D is electron dose. Therefore it will be impossible to remove the effect of the electron beam completely but there are some ways to reduce and mitigate it as much as possible. These are summarized from the group discussion as:

- An accurate measure of electron dose must be obtained for every experiment. There is currently no standard way to perform this in the electron microscope, unless the user specifically purchases separate equipment. The microscope manufacturers have been asked to provide Faraday cups as standard for future microscopes, and to be able to retrofit

existing microscopes with a Faraday cup in the selected area diffraction aperture location.

- A systematic study of varying dose and primary electron energy should be performed by the user for each new material system that is to be studied to find the regime that balances resolution against materials change. For example, systematic study of effect of incident electron energy, electron dose, and irradiation temperature was used to characterize the atomic structure, the electronic structure and thermal stability of Si to conclude that electron beam induced amorphization of Si occurred not by accumulation of point defects but by a cascade of small changes (Figure 4).[43] While it is hard to define one standard of the “beam damage” condition for all materials, the user will get a good understanding of which dose to work with if this systematic variation is performed. It will be beneficial to check these doses at the temperatures, pressures, and in liquids that are desired for an experiment, as these can quite often be different than for vacuum conditions.
- We must begin to communicate the total electron dose used for all experiments in publications and presentations.
- As leaders in the field of electron microscopy, it is our responsibility first and foremost to teach new users (students and new users in the field) about the possible adverse effects of the electron beam.
- We recommend that we consider creating a database for the best electron dose that a user has found for a particular material, support, temperature, pressure, type of camera (detection system) etc. It is a daunting task as there are so many variables but if the community starts to report the conditions used for each experiment, we can start building it. We suggest applying for funding to start the database for some standard samples, and once established, continue to grow it with input from users around the world. In this way, a new electron microscopy user can immediately gain perspective on the dose ranges to be used for specific experiments. It will also speed up experiments for experienced microscopists performing work on a new material system for the first time.

2.1.2. Drift-correction—Drift is major issue for all *in situ* experiments, especially during heating. Although new MEMS based heating holders have minimal drift (< 1 nm min^{-1}, at best), it is still enough to make continuous acquisition of high resolution images during heating difficult. Both hardware and software development are needed. Currently some individual labs have addressed this issue, e.g., there is one system developed in in Graz, Austria, another in Australia and National Center for Electron Microscopy (NCEM), Berkeley has a lot of great links for drift correctors, but it needs to be universally available. TEM manufactures should consider incorporating drift correctors, similar to the one for tomography on all TEM platforms.

2.1.3. Temperature measurement—Temperature measurement continues to be one of the challenging problems that has kept us from obtaining thermodynamic and kinetic information. The actual temperature of the sample under TEM observation has been a big question over the years. The ambiguity for furnace heaters with thermocouples arises from the nature of thermal contact between TEM grid and furnace, and the thermal conductivity of grid material and sample. For ETEM experiments the problem becomes more severe as temperature gradients and rates are also dependent on gas composition and pressure.

Again, there are some efforts directed to mitigate this problem but a universally available solution is still to be realized. For example, the Delft group has used electron energy-loss spectroscopy (EELS) to measure local temperature, using change of gas density with temperature in windowed holder filled with 1.2^5 Pa of H_2.[44] Resistivity measurements as implemented in the Delft-MEMS based holders seem to work quite well. Since the workshop, measurement of the Ag expansion coefficient[45] and the incorporation of Raman spectroscopy (correlative microscopy, see section 3.1.6) has been used for *in situ* temperature measurement in vacuum and gas environments.[19] Our wish list for future is:

- *In situ* temperature readout available for heating and cooling holders (has been addressed by recent heating chip devices).
- Accuracy of temperature measurement to be within ± 5 °C.
- Accessible temperature range of −170 °C to 1500 °C.
- Spatial resolution: even if homogenous temperature within the sample area is guaranteed, local temperature can be used for nanocalorimeter and for that micrometer scale can be a good start.
- Accurate measurement of low temperatures (Liquid He to liquid N_2 temperature). For low temperature, the accuracy of measurement is vital as a difference between 4 K and 10 K may have significant consequences.

2.1.4. High temporal resolution for recording media—High spatial resolution combined with high temporal resolution is required to identify transient reaction products, understand catalytic reaction mechanisms, etc. Currently available image acquisition systems allow us routinely to acquire high-resolution (< 0.1 nm) images with low temporal resolution (0.033 s to 0.2 s range) or low resolution (a few nanometer in single shot mode) with high temporal resolution. However, a number of *in situ* measurements such as catalysis, nucleation, etc. not only require high spatial and temporal resolution but also a large field of view for better statistics. As mentioned earlier, the current limitation for collecting images with low exposure time (high speed) is due to poor DQE of the CCD cameras that require a high electron dose to meet the Rose criteria. But high electron dose can alter the reaction process due to heating or knock-out damage. Direct electron detection camera based on complementary metal-oxide semiconductor, (CMOS) technology can improve temporal resolution without compromising the spatial resolution. With a DQE of 0.3 to 0.7 (compared to < 0.1 for CCD), frame acquisition rates of 200 s^{-1} to 1600 s^{-1} have been demonstrated and can be improved to a rate of 3000 s^{-1} in 5 years to 10 years. Moreover, data transfer and data handling speed make usage laborious, and the cost of these cameras is too high, making

widespread application difficult. Also, there is still space for improving the DQE and thereby improving temporal resolution for dynamic imaging. Following are suggested ways to achieve high temporal resolution to acquire atomic scale images and spectra:

- Detectors for readout between 10^{-6} s to 10^{-3} s
- Gated stroboscopic mode for sources – run as continuous source or as pulsed source.
- Brighter electron source to improve SNR for fast acquisition.
- EELS detector: the same detector can be used for EELS, but it is desirable to revert to the older Quantum model, * which permits spectra collection rate of 1000 s^{-1}.
- For energy-dispersive x-ray spectroscopy (EDX), both FEI* and JEOL* have 1 sr. collection angle systems available. FEI* has a 4 detector system called ChemiSTEM/Talos, * and JEOL* has 1 detector system. Both will negate the need for tilting samples for best signal collection, making it possible to collect data in combination with windowed liquid and heating holders.

2.1.5. Data acquisition and processing—We anticipate that the desired high spatial and high temporal resolution will come with a problem of data transfer, storage and processing. For example, (1024 x 1024) pixel images collected at a frame rate of 400 s^{-1}, will generate approximately 4 Terabytes (TB) s^{-1}. This data needs to be transferred to a storage device quickly and each frame needs to be processed to follow the atomic scale changes occurring with high temporal resolution. In other words, data acquisition, storage, data mining and processing needs to be developed by engaging interdisciplinary community (including software engineers). The following actions should be taken to address this issue:

- Fast data transfer platform (some progress has been made by Gatatn K-2 camera* users).
- Fast processor (64 bit)
- Develop loss-less compression techniques.
- Linking stimuli (temperature, gas pressure, etc.) to the data set.
- Integration of data and automated analysis of crystallographic orientation mapping for images and diffraction – generate a list of possible phases – elements present.
- Batch processing of images from movies in 2 GB sections.
- Need intelligent principle component analysis (PCA) for image analysis.
- Crowd Sourcing for Intelligent Processing of Large Data Sets.
- Artificial intelligence with manual input from user –machine intelligence
- Need some crowd sourcing – community to share data – identify ways to set it up?

Some of these issues are currently being addressed by the groups who are using direct detectioncameras, such as Gatan's K2.*

2.1.1. Concurrent Microscopy and Spectroscopy (lab in the polepiece gap)—*In situ* observations of the effects of external stimuli on the morphology, structure, chemistry have enabled us to elucidate a number of atomic scale reaction mechanisms. However the information obtained is limited to the nanoscale, and in order to relate the local behavior (in the electron beam) to the average behavior of the sample, simultaneous acquisition of complementary integrated measurements are needed. The trend anticipated for *in situ* TEM for the next decades is that the complexity of experiments performed in a TEM will increase to achieve realistic conditions.

The incorporation of other complimentary stimuli and detectors for *in situ* experiments on present transmission electron microscopes is limited by the polepiece gap of the objective lens where the sample is located. For uncorrected or spherical aberration corrected objective lenses, a compromise between spatial resolution and the width of this gap has to be made. Sub 0.1 nm resolution can be achieved without aberration correction only for lenses with a gap width of about 2 mm to 3 mm which is too small for many *in situ* experiments. Spherical aberration correction with monochromation or chromatic aberration correction removes these restrictions as has been proven by the TEAM I instrument* at Lawrence Berkeley National Laboratory (LBNL) that achieves 0.05 nm resolution with a 5 mm pole piece gap. More experimental parameters have to be controlled and measured (multimodal/ multiscale measurements) that could be in the form of a built-in Raman spectrometer, secondary ion mass spectroscopy (SIMS) or other types of (optical) spectroscopy.[19, 46] Opening up the polepiece gap will leave more room near the sample to include additional probes and detectors, e.g. tomography plus one or more of the following capabilities: (a) Environmental cell (with windows); (b) Heating, cooling, (c) Nano-biasing, and (d) Cryo box for frozen samples.

Tomography alone can be done with a gap of 5 mm or less. If combined with one or more of the other functions mentioned above, we will require a wider and thicker sample holder tip which then needs a wider pole piece gap to achieve high tilt angles. We can further envision incorporating other probes such as optical, x-ray, etc. to make micron-scale measurements combined with atomic scale imaging and spectroscopy. This type of stage is important for scientific challenges in catalysis and electrochemistry (and others). On the other hand, an objective polepiece with a 10 mm gap results in about eight times the volume available for in-situ instrumentation (depending on the area in the xy-plane usable for a certain experiments) and contrast transfer calculations for this lens in combination with a C_c-corrector show that a spatial resolution of better than 0.07 nm can be expected (Figure 5).[47] An alternative approach to C_c correction is the combination of spherical aberration correction with a monochromator. This concept allows similar resolution at the cost of a strongly deformed beam.

Aberration correction is undoubtedly helpful in improving the contrast transfer behavior at high spatial frequencies but it degrades contrast transfer at low spatial frequencies (> 0.05 nm). The combination of chromatic aberration correction and phase plate imaging can

mitigate this issue.[48] A typical Lorentz lens has much higher aberration coefficients than even the wide gap objective lens discussed above, which limits the resolution to about 2 nm. Chromatic and spherical aberration correction enables atomic level resolution even for a Lorentz lens but the contrast for spatial frequencies relevant for imaging e.g. magnetic vortices is very small. Phase contrast promises optimum contrast on this size scale while maintaining high contrast transfer for high-resolution TEM. As a consequence, the atomic and the magnetic structure of a sample can be imaged at the same time.

2.1.2. Simultaneous Acquisition of images and diffraction patterns—Combining diffraction and imaging information would be a valuable tool for many applications: e.g. catalytic particles. At present, parallel detection of both signals is not possible and requires a different TEM design. Modification of current instrumentation will allow switching between diffraction and imaging mode with sufficient speed. This can be done with software but requires two detectors.

Recording diffraction patterns with CCD cameras is still not satisfactory. Present CCD cameras have a depth of 16 bit which is not sufficient for the dynamic range for diffraction patterns. Detecting image and diffraction pattern have completely different dynamic ranges; necessitating 24 bit dynamic range capable of *in situ* acquisition. We expect that development of detectors with readouts 10^{-6} s to 10^{-3} s in 5 to 10 years from now is feasible.

2.2. Challenges relevant to Specific Research field

2.2.1. Scientific challenge in catalysis—TEM is ideally suited to characterize catalyst nanoparticles before and after reactions. Recent advances in TEM column modification and holder design has now made it possible to observe dynamic processes under near-reactor (ETEM) or reactor (using windowed holder) conditions. Atomic-scale imaging and spectroscopic analysis can now be performed under *operando* conditions. [49–51] In order to understand the catalytic process we need to (a) follow the structural and compositional changes and their relationship to the activity of individual nanoparticles and (b) identify the reactive sites/surfaces. However, the image intensity and thereby resolution deteriorates severely as a function of pressure when using high atomic number gasses such as oxygen or nitrogen (Figure 6).[52]

In order to effectively investigate catalytic processes, this we need:

1. Instrumentation capable of providing high resolution imaging and spectroscopy data under reactor conditions (atmospheric pressure or above).
2. High temporal resolution to reveal instantaneously events occurring during catalysis.
3. The ability to observe 3-D structure evolution instead of 2-D images in projection to understand substrate-particle interaction and dynamic shape changes during reaction.

4. Measurements of the change in gas composition during reaction (in *operando* condition).

5. Incorporation of aberration-correctors for the probe-forming optics, in order to enhance high angle annular dark field (HAADF) STEM resolution to the sub-0.1 nm level. This is critical for imaging the small clusters (single atom or several atoms) that often control catalysis.

In summary, a combination of high pressure cells, high spatial and temporal resolution, high-tilt holder (or large pole-piece gap) are required. When these requirements are met, tomography can be performed intermittently for reactions that take more than an hour. During dynamic imaging, the state of the sample could be stabilized by lowering the temperature while the gaseous environment is still maintained.

2.2.2. Scientific challenges in electrochemistry—The first electrochemical cell was fabricated and successfully used to observe electrochemical deposition of Cu on gold surface in 2003.[12] Although liquid cell holders are now routinely used for *in situ* observation of electrochemical processes resulting in nucleation and growth of nanostructures, very little progress has been made towards developing a robust and versatile electrochemical cell until recently.[53] Such a cell is essential for understanding the factors controlling to the lifetime and energy density of batteries. A controlled electrochemical experiment needs three electrodes with electrical connections, temperature control a windowed cell, and two reservoirs if the electrolyte is liquid. Electrochemical reaction rates depend strongly on temperature. Temperature control with a stability of a few degrees is therefore required. This will likely add to the bulk of the stage and depends on accurate temperature measurement). Electrochemical reactions which are limited by diffusion of ions to and from the electrode surface require control of the thickness of the diffusion layer in the electrolyte. This can be achieved by controlling the flow rate of the electrolyte (difficult in present liquid cells) or by rotating electrodes. Both methods will increase the bulk of the stage. Future developments in cells are required to:

- Understand the nature of the over potential.
- Understand the structural and chemical changes in electrodes during charging and discharging.
- Characterize nanostructured electrolytes and electrodes.
- Measure diffusion in electrodes and electrolyte,
- Identify growth mechanisms during electro-deposition.
- Understand microstructural changes in complex electrodes during charging/discharging (3D structure is important for all these experiments).

Temporal resolution can be increased using pulsed electron sources that will naturally lead it electrochemistry to be one of the DTEM applications.

2.2.3. Scientific challenges for Phase transformations—Ultrafast TEM or DTEM (section 1.2.3) is currently being used to capture phase transformation mechanisms. The following scientific challenges were identified:

1. Verification of predicted intermediate states in liquid before solidification.
2. Identification of transient reaction products.
3. Determination of catalytic reaction mechanisms.

Neither the stroboscopic nor single shot approach, currently used, is capable of meeting these challenges and requires further development. There is a gray area in correlating the interval between the laser pulse and acquisition time with high precision. Moreover, no spectroscopy option is currently available on the DTEM platform. The Boersch effect leads to an incident beam with large energy spread. It has been proposed that by lengthening the pulse so that electron-electron interactions are minimized, 1 eV energy resolution could be achieved in μs, but this has not been verified. In a 10 ns pulse billions of electrons can be generated, but the beam is not very coherent or bright (10 A sr^{-1}). In addition, for events having periods between 10^{-3} s to 10^{-6} s, there is no chance of acquisition as the pulse duration in current DTEM cannot be longer than 1 μs. In any case, for current systems higher electron doses will be required to combine high spatial resolution with high temporal resolution. But the beam damage will be a major concern under such conditions.

4. CONCLUSIONS

Most of the participants were currently employing one of the nine instrumentation platform identified during the workshop (Figure 7a), with heating holders being most popular. Workshop participants identified scientific challenges that need to be addressed in the future in the area of catalysis, electrochemistry, phase transformation and mechanical property measurements. The following instrument/software developments are required to meet these challenges:

1. High spatial and temporal resolution combined on the same platform.
2. Automatic drift correction
3. Temperature measurement at the microscale.
4. Simultaneous acquisition of bright-field/dark-field/selected area diffraction pattern (BF/DF/SAEDP).
5. Combinatorial holders to measure the mechanical properties of aligned crystals (double-tilt) as a function of temperature (heating), biasing (electrical/magnetic)

It is interesting to note that most of the participants identified data acquisition and processing were to be the area where future developments are needed (Figure 7b). A summary of these findings is given in Table 1.

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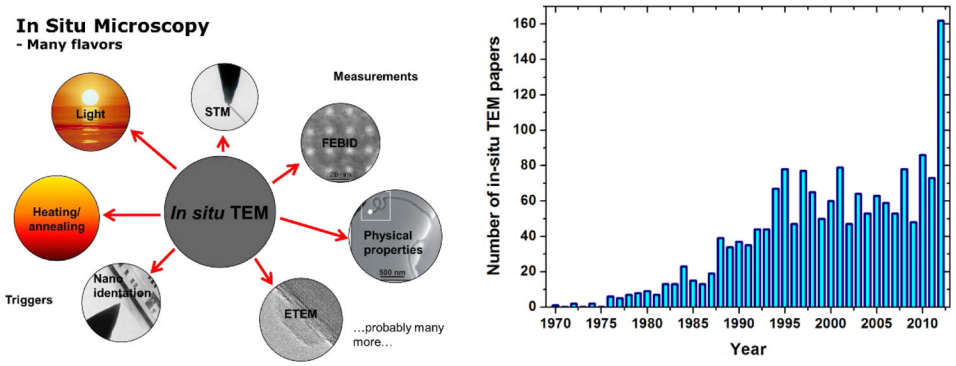

Figure 1.

(a) External stimulii currently used for in situ observations on a TEM platform, (b) growth in number of publication during 1970 and 2012 (Sinclair, MRS Bull. (2013)) .[1]

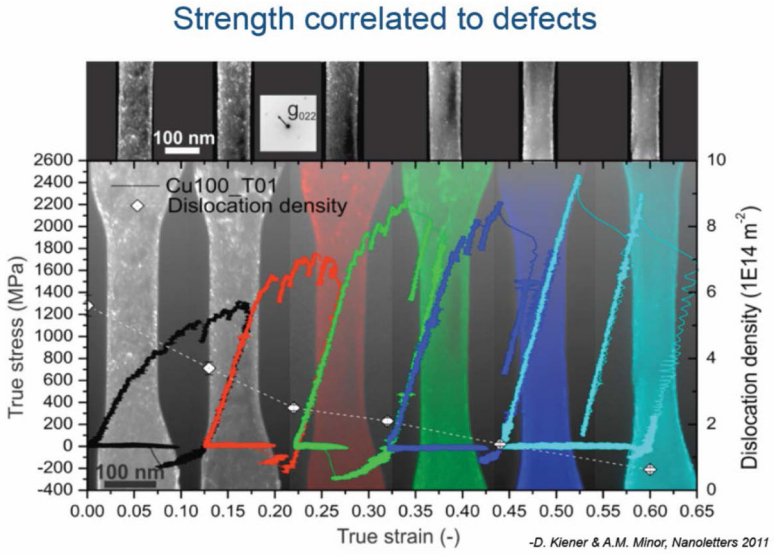

Figure 2.

True stress versus true strain data for repeated loadings of an initially 133 nm diameter tensile sample in (100) orientation. The specimen yields at 636 MPa and shows significant hardening during elongation to 65 % true strain. Simultaneously, the dislocation density (defects can be seen as bright features in the upper row of dark field images) as denoted by the white diamond symbols and the right-hand axis of the graph is reduced by an order of magnitude. Correspondingly the deformation characteristics becomes more stochastic as the defect density decreases (Kiener et al., Nano Lett. (2011).[9]

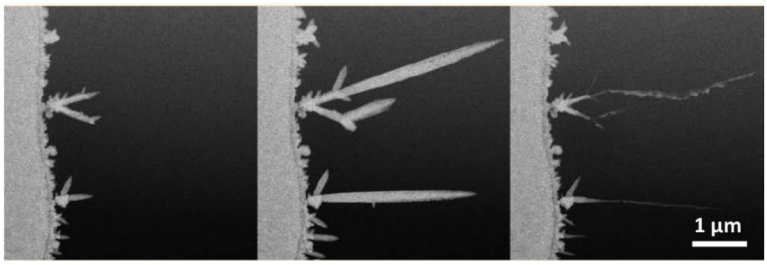

Figure 3.

Dendrite growth and collapse during voltage cycle from lead nitride solution in a liquid cell (White et al., ACS Nano (2012).[22]

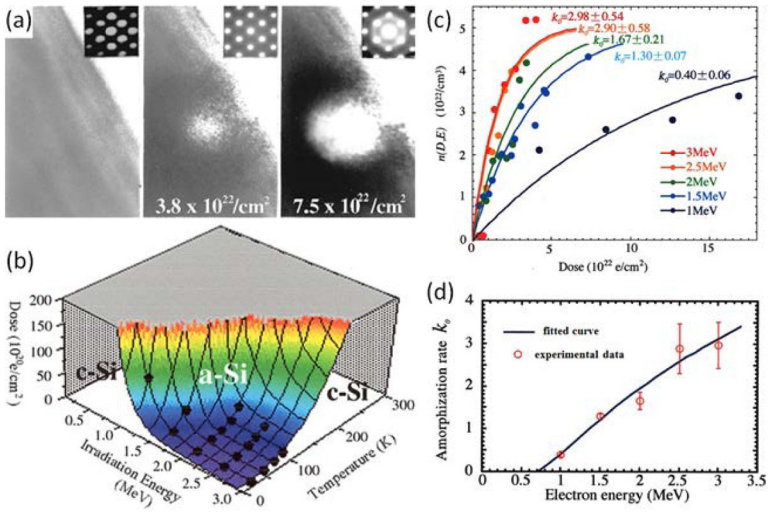

Figure 4.

An in situ TEM analysis of the amorphization of crystalline silicon triggered by electron irradiation. Systematic and quantitative data acquisition as a function of electron energy, dose and sample temperature (a) and (b) combined with a theoretical model predicting the volume of amorphous embryo that is created by the impact of an energetic electrons (c) and (d.

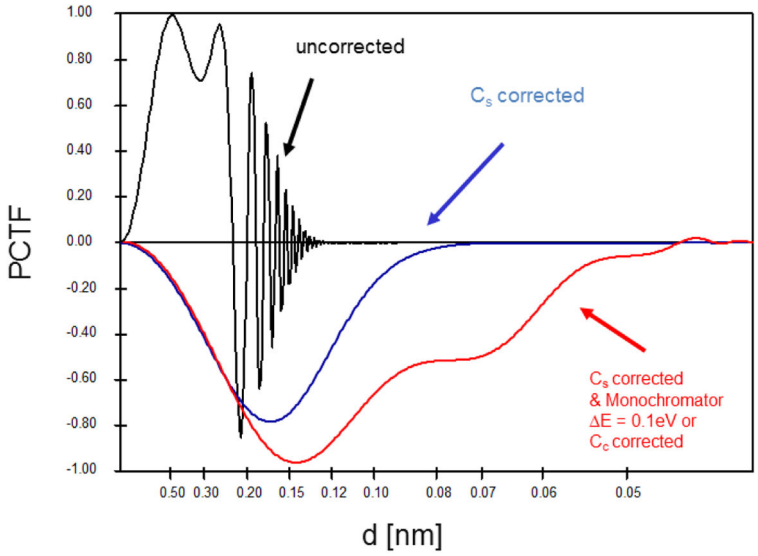

Figure 5.
Contrast transfer functions for a 300 kV instrument with an objective lens gap width of 10 mm.

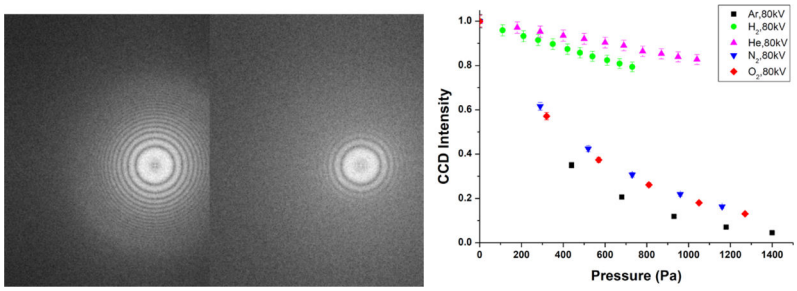

Figure 6.

Loss of information limit can be estimated using fast Fourier transform (FFT) of amorphous carbon film (a) in vacuum and (b) in 1700 Pa of Ar. (c) Loss of intensity as a function of pressure for different gasses (Courtesy: Jakob Wagner)[52]

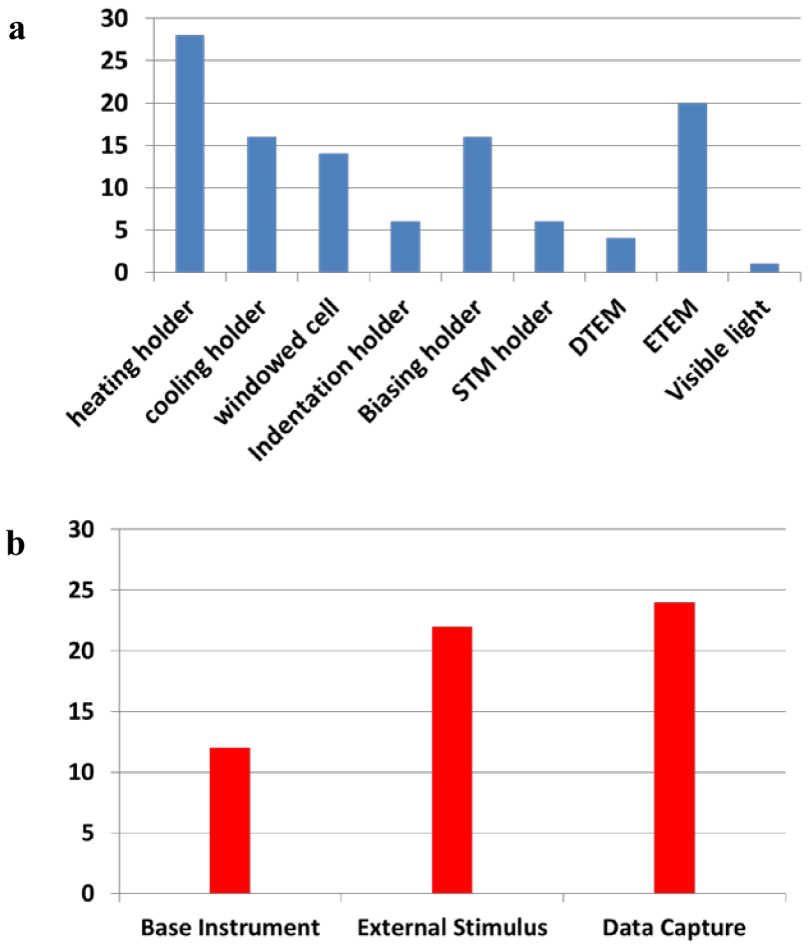

Figure 7.

(a) Number of participants using various instruments/techniques for in situ measurements and (b) area of improvement identified for successful experiments as needed to advance the state of the art.

Table 1

Summary of Future Developments needed to address unresolved scientific issues.

Category	Current Applications	Suggested Improvements	Scientific challenges
Heating holders	√ Phase transformation √ Gas-solid reactions √ High temperature electrochemistry √ Nucleation and growth of Precipitates	• Higher temperature limit • Local, precise Temperature measurement • Uniform temperature across the sample grid/chip	• Phase transformations in ceramic materials. • Nanoscale kinetic and thermodynamic measurements
Indentation Holders	√ Mechanical property measurement. √ Structure- property relationship. √ Stress induced phase transformation.	• Higher mechanical stability for high magnification tests • Versatile testing modes, such as compression, tensile, bending etc. • Coupling with thermal/electrical/gas fields. • Different tip geometries and grip styles, e.g., for doing tensile experiments different sample geometries	• Noises resulted from both the instruments and the environment • Thermal drift upon heating. • Decouple the effects from different sources, like e-beam, thermal etc. 3-D stress state analysis as a function of crystal orientation
Liquid cell holders for electrochemistry	√ In-situ synthesis. √ Liquid-solid interactions Liquid electrochemistry	• Robust windows. • Uniform thickness for entire viewing region Heating in liquid	• Nucleation and growth mechanisms. • Phase transformations of solid materials in liquids. • Improve life time of batteries by understanding electrode poisoning.
High pressure gas cells with heating device	√ Gas solid reactions. √ Catalytic reactions atmospheric chemistry climate research.	• Robust windows. • Temperature measurement. • Gas Composition measurement.	• Nanoscale kinetic and thermodynamic measurements. • Heterogeneous catalysis. • Gas-solid reactions involving corrosive and/or contaminating gases. • Understand the sites for catalytic reactions, Improve efficiency.
High gas pressure ETEM Emission source/Electron gun	√ Catalytic reactions. √ Gas effect on mechanical properties. √ Gas-effect on electrical resistance.	• High pressure and high resolution. • Integration with spectroscopic techniques High energy resolution High intensity	• Controlled nanostructure growth • Beam-induced contamination in TEM parts •Interaction of e-beam, materials and gases • Understand ice nucleation in aerosols
Ultrafast TEM	√ Phase transformation in a few systems.	• Better time resolution in movie mode, more images in a movie, higher spatial resolution, more *in situ* capabilities	• Understand the nucleation of phase transformation on an atomistic level. • Application to radiation sensitive systems in soft matter research.
Concurrent Microscopy and spectroscopy: Large polepiece gap	√ Not available.	• Multi-probes. • High tilt tomography.	• Perform complex chemical experiments completely inside a TEM -> better understanding of chemical and electrochemical reactions
High speed data acquisition	√ *In situ* nucleation and growth of nanostructures.	• High spatial and high temporal resolution. • Embedment of metadata of *in situ* parameters.	Understanding of defect dynamics in 2D materials Controlled nanostructure growth