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Review article

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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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 (Fig. 1a). Research interest in this area is reflected in (a) an exponential growth in number of publications over last 3 years (Fig. 1b) [1], (b) the fact that each major materials related conference has at least one session related to in situ TEM, and (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 that are currently available, and what future advancements are needed to address them to further the 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 an 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. Carefully designed experiments [3] result in unprecedented amount of scientific knowledge that requires automated data processing and evaluation procedures.

2. 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

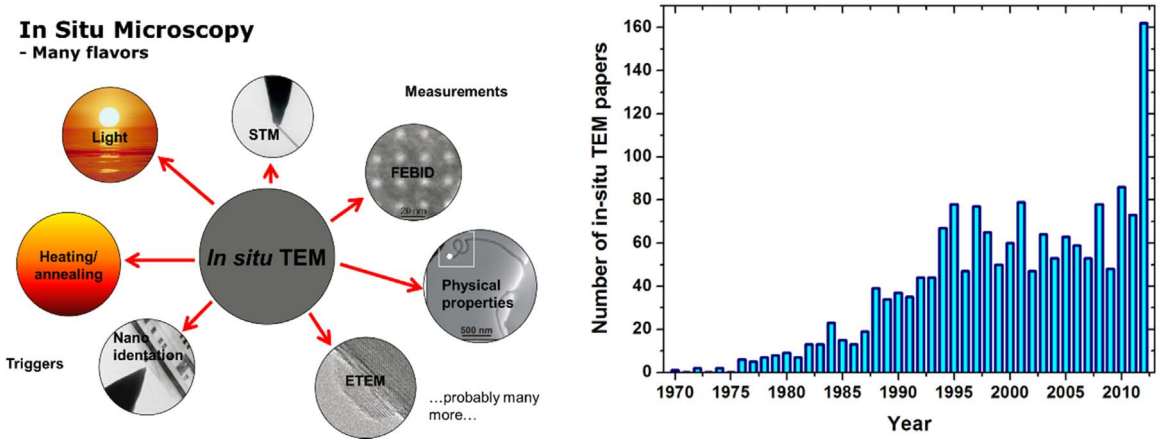

Fig. 1. (a) External stimulii currently used for in situ observations on a TEM platform, (b) growth in number of publication during 1970 and 2012 (Sinclair, MRS Bull. (2013)) [1].