IN SITU OBSERVATIONS OF THE DYNAMICS AT NANOSCALE BY ULTRAFAST TRANSMISSION ELECTRON MICROSCOPY

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As a continuous solid crystal is reduced in scale to a system of small number of atoms, its behavior often changes considerably. This can lead to interesting optical, electronic, magnetic, and catalytic properties. A significant amount of effort has been expanded, particularly over the last two decades, on characterizing the size-, quantum- or surface states-effects to which these changes are generally attributed (1-4). The possibility of tailoring the properties of nanomaterials has lead to some interesting discoveries and potential applications in medicine, energy conversion and storage, catalysis, sensing, electronics, etc. To harness the properties of such novel systems, however, a better understanding needs to be developed on their structure and the effect on the nanomaterials' properties.

The equilibrium states of most materials are well known and have been probed by large variety of techniques. Information on the intermediate states, however, is not complete. To reveal the process of structural transformation and to understand the dynamics, a description of the states during a structural transition is need with temporal resolution in the nanosecond to femtosecond range. At present, there is no well-developed general method for the atomic-level structural determination of short-lived transient states.

For ultrafast studies of structural transition, X-ray and electron diffraction are generally employed. Despite their high spatial resolution, they visualise the reciprocal space, thus giving information on presence or absence of periodical structure. As shown in figure 1, however, a combination of high temporal resolution and real space imaging are required for the study of processes such as nucleation, interphase boundary motion, shock propagation, radiation damage, solid state chemical reactions (5-9). This prompts the necessity of a new method that can provide real space imaging with high temporal and spatial resolution.

The transmission electron microscope (TEM) is a powerful and versatile tool for characterisation of the materials offering high spatial resolution (as low as 0.5Å (10; 11)); but due to the poor temporal resolution, it is rarely used for in situ direct imaging of structural transitions. Limited by the video capture rate of the camera, the images are usually acquired in seconds-scale. In this presentation, we will outline recent work on the modification of a TEM to obtain a Dynamic TEM (DTEM). By improving the temporal resolution we can reveal the dynamics of non-reversible processes of structural transitions (12-14). Challenges and advantages of such modification will be described in the context of our initial results on amorphous Silicon and Germanium nucleation. The TEM modified at INRS is the first DTEM in Canada.

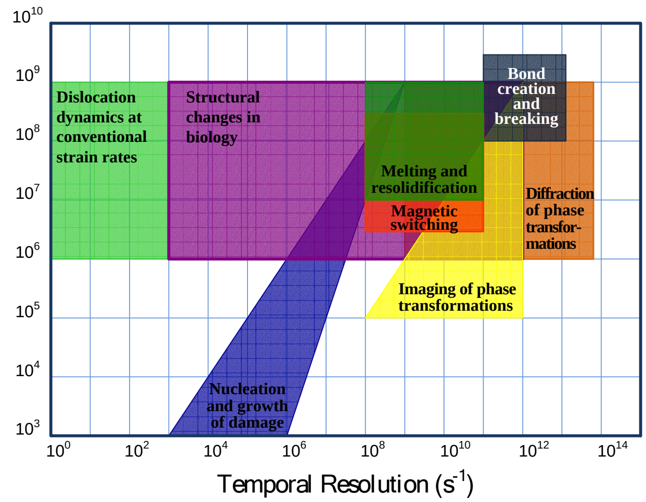

Figure 1 (5)

Bibliography

1. **F. Rosei.** Nanostructured surfaces: challenges and frontiers in nanotechnology. *Journal of Physics: Condensed Matter.* 2004, Vol. 16, pp. S1373–S1436.

2. **J.W. Reiner, F.J. Walker and C.H. Ahn.** Atomically Engineered Oxide Interfaces. *Science.* 2009, Vol. 323, pp. 1018-1019.

3. **L. Nikolova, R.G. Saint-Jacques, C. Dahmoune, and G.G. Ross.** Silicon nanoparticle formation in SiO2 by Si ion implantation : effect of energy and fluence on size distribution and on SiOx composition. *Surface and Coatings Technology.* 2009. Accepted article. To be published in Special issue on SMMIB15. Available online Ref #SCT14881.

4. G. **Schmid and B. Corain.** Nanoparticulated gold: Syntheses, structures, electronics, and reactivities. *European Journal of Inorganic Chemistry.* 2003, Vol. 17, pp. 3081-3098.

5. **W.E. King, G.H. Campbell, A. Frank, B. Reed, J.F. Schmerge, B.J. Siwick, B.C. Stuart, and P.M. Weber.** *Journal of Applied Physics.* 2005, Vol. 97, 11, p. 111101.

6. **J.S. Kim, T. LaGrange, B.W. Reed, M.L. Taheri, M.R. Armstrong.** Imaging of Transient Structures Using Nanosecond in Situ TEM. *Science.* 2008, Vol. 321, pp. 1472-1475.

7. **J.M. Thomas.** A Revolution in Electron Microscopy. *Angewandte Chemie.* 2005, Vol. 44, pp. 5563 – 5566.

8. **O.-H. Kwon, B. Barwick, H.S. Park, J.S. Baskin, and A.H. Zewail.** 4D visualization of embryonic, structural crystallization by single-pulse microscopy. *PNAS.* 2008, Vol. 105, 25, pp. 8519–8524.

9. **M.L. Taheri, B.W. Reed, T.B. LaGrange, and N.D. Browning.** In situ laser synthesis of Si nanowires in the dynamic TEM. *Small.* 2009, Vol. 4, 12, pp. 2187-2190.

10. **C. Kisielowski, B. Freitag, M. Bischoff, H. van Lin, S. Lazar, G. Knippels, P. Tiemeijer, M. van der Stam, S. von Harrach, M. Stekelenburg, M. Haider, S. Uhlemann, H. Müller, P. Hartel, B. Kabius, D. Miller, I. Petrov, E.A. Olson, T. Donchev, E.A. Kenik, A.R. Lupini, J. Bentley, S.J. Pennycook, I.M. Anderson, A.M. Minor, A.K. Schmid, T. Duden, V. Radmilovic, Q.M. Ramasse, M. Watanabe, R. Erni, E.A. Stach, P. Denes and U. Dahmen.** Detection of Single Atoms and Buried Defects in Three Dimensions by Aberration-Corrected Electron Microscope with 0.5-Å Information Limit. *Microscopy and Microanalysis.* 2008, Vol. 14, pp. 469-477.

11. **D. J. Smith.** Development of Aberration-Corrected Electron Microscopy. *Microscopy and Microanalysis.* 2008, Vol. 14, pp. 2-15.

12. **O. Bostanjoglo, R. Elschner, Z. Mao, T. Nink, and M. Weingärtner.** Nanosecond electron microscope. *Ultramicroscopy.* 2000, Vol. 81, pp. 141-147.

13. **M.R. Armstrong, K. Boyden, N.D. Browning, G.H. Campbell, J.D. Colvin, W.J. DeHope, A.M. Frank, D.J. Gibson, F. Hartemann, J.S. Kim, W.E. King, T.B. LaGrange, B.J. Pyke, B.W. Reed, R.M. Shuttlesworth, B.C. Stuart, and B.R. Torralva.** Practical considerations for high spatial and temporal resolution dynamic transmission electron microscopy. *Ultramicroscopy.* 2007, Vol. 107, pp. 356-367.

14. **T. LaGrange, K. Boyden, C.G. Brown, G.H. Campbell, J.D. Colvin, W.J. DeHope, A.M. Frank, D.J. Gibson, V.F. Hartemann, J.S. Kim, W.E. King, P.J. Pyke, B.W. Reed, M.D. Shirk, R.M. Shuttlesworth, B.C. Stuart, B.R. Torralva, and N.D. Browning.** Single-shot dynamic transmission electron microscopy. *Applied Phisics Letters.* 2006, Vol. 89, pp. 044105-044107.