

Three-dimensional Observation of Carbon Nanostructures with Confocal Scanning Transmission Electron Microscopy

A. Hashimoto^{*}, M. Shimojo^{**,***}, K. Mitsuishi^{****} and M. Takeguchi^{*****}

^{*} International Center for Young Scientists, National Institute for Materials Science, 1-2-1 Sengen, Tsukuba 305-0047, Japan

^{**} High Voltage Electron Microscopy Station, National Institute for Materials Science, 3-13 Sakura, Tsukuba 305-0003, Japan

^{***} Advanced Science Research Laboratory, Saitama Institute of Technology, 1690 Fusaiji, Fukaya 369-0293, Japan

^{****} Quantum Dot Research Center, National Institute for Materials Science, 3-13 Sakura, Tsukuba 305-0003, Japan

^{*****} Advanced Nano-characterization Center, National Institute for Materials Science, 3-13 Sakura, Tsukuba 305-0003, Japan

Three-dimensional (3D) imaging has been an indispensable technique in various industrial and scientific fields. Recently, confocal scanning transmission electron microscopy (STEM), which is based on applying the principles of confocal imaging to transmission electron microscopy (TEM), has attracted considerable interest as a promising depth-sectioning and 3D imaging technique [1-6], along with computed tomography and aberration-corrected STEM. Confocal STEM imaging has been demonstrated by Zaluzec and his coworkers [1,2]. However, 3D imaging with confocal STEM has not yet been performed because of some practical difficulties. We employed a stage-scanning system in order to overcome the difficulties [5,6]. By using the system, only a specimen is moved three-dimensionally under a fixed confocal lens configuration. However, obtained confocal STEM images did not demonstrate a significant improvement in the depth resolution. Further, theoretical studies have reported that the interpretation of confocal STEM images is not straightforward because of nonlinear phase contrast transfer [7,8]. In this work, we propose dark-field STEM imaging under the confocal condition by using an annular-dark-filed (ADF) aperture. Furthermore, we observed carbon nanostructures with confocal ADF-STEM to perform 3D imaging.

Figure 1 shows a schematic diagram of the confocal ADF-STEM system. A conventional TEM equipped with a STEM module (JEOL Ltd.: JEM-2100F, Cs = 1.0 mm) and piezo-driven specimen holder were used for confocal STEM imaging. The specimen holder was modified and controlled by computer programming for stage scanning along the X, Y and Z axes. In the upper configuration, a condenser lens creates a well-focused probe in a specimen, and in the lower one, an imaging lens magnifies and projects an image of the probe on a STEM detector. Detected signals were synchronized with the specimen displacement and displayed on a computer screen as a stage-scanning STEM image. The annular aperture was made from a Mo foil using a focused ion beam technique and arranged under the specimen to cut off the direct beam and select only scattered electrons. Depth sectioning was performed by rejecting electrons from the out-of-focal plane in the specimen with a pinhole aperture in front of the detector.

Figures 2 (a) and (b) show X-Y and X-Z slice images of Au particles on an amorphous carbon film, respectively. In the X-Y scan image, Au particles with diameter of 5 nm were observed as well as a conventional dark-filed STEM image. The X-Z slice image of region indicated by arrows in the X-Y image showed the elongated Au particles along the Z axis. It was found that the particles were detected at the restricted Z position. This indicated that confocal ADF-STEM imaging drastically

improved the depth resolution and had a potential for depth sectioning. Furthermore, we took image sequences of carbon nanostructures by changing the Z specimen position and reconstructed their 3D structures.

References

- [1] S.P. Frigo et al., *Appl. Phys. Lett.* 81 (2002) 2112.
- [2] N.J. Zaluzec, *Microsc. Today* 6 (2003) 8.
- [3] P.D. Nellist et al., *Appl. Phys. Lett.* 89 (2006) 124105.
- [4] J.J. Einspahr and P.M. Voyles, *Ultramicroscopy* 106 (2006) 1041.
- [5] A. Hashimoto et al., *e-J. Surf. Sci. Nanotech.* 6 (2008) 111.
- [6] M. Takeguchi et al., *J. Electron Microsc.* 57 (2008) 123.
- [7] K. Mitsuishi et al., *Ultramicroscopy* 108 (2008) 981.
- [8] E.C. Cosgriff et al., *Ultramicroscopy* 108 (2008) 1558.
- [9] A part of this research was financially supported by Grant-in-Aid for Scientific Research of Japan Society for the Promotion of Science, Japan.

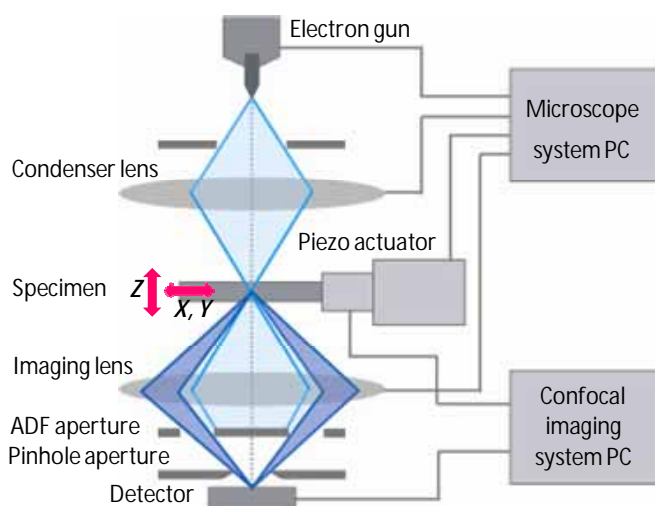


FIG.1 Schematic drawing of confocal ADF-STEM with a stage-scanning system.

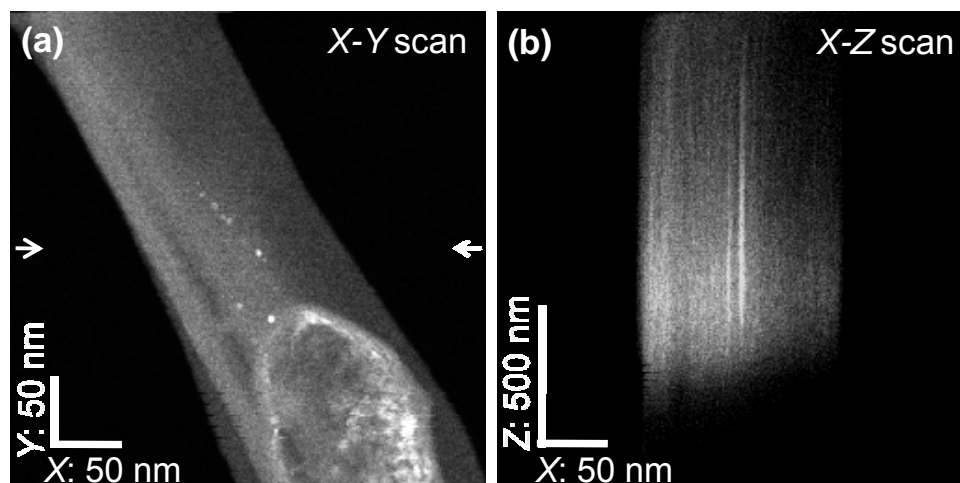


FIG.2 Confocal ADF-STEM image of Au particles on a carbon film. (a) X-Y slice image. (b) X-Z images of region indicated by arrows in the X-Y image.