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Three-dimensional Confocal Imaging Using Coherent Elastically Scattered Electrons

Changlin Zheng[1], Lazar Sorin[2], Ye Zhu[3] and Joanne Etheridge[1,4]

[1.] Monash Centre for Electron Microscopy, Monash University, Victoria, Australia
[2.] FEI Electron Optics, 5600 KA Eindhoven, the Netherlands
[3.] Department of Applied Physics, the Hongkong Polytechnic University, Hong Kong, China
[4.] Department of Materials Science and Engineering, Monash University, Victoria, Australia

The properties of advanced materials depend strongly on their three-dimensional (3D) structure. Conventional TEM/STEM provides a two dimensional representation of this 3D structure that depends in a complex way on dynamical scattering, making information about the third dimension along the optic axis difficult to extract. Several methods have been developed in an effort to circumvent this problem and provide 3D information, including electron tomography, physical and optical sectioning.

Electron tomography has proved extremely powerful for materials characterization. It records a series of two-dimensional projection images at different specimen orientations for reconstruction into a 3D image. However, both the data recording and reconstruction can be time consuming and the accumulative radiation dose can be high.

In optical sectioning, the 3D object is reconstructed directly from a sequence of two-dimensional images taken at different focal points along the optic axis. In optical microscopy, scanning confocal fluorescence microscopy is one of the most successful optical sectioning modes for 3D imaging of biological samples [1]. The improvement in depth resolution derives from the incoherent imaging mechanism. Recently the confocal mode has also been introduced into electron microscopy [2], with further advances arising with the introduction of double-aberration-corrected STEMs e.g. [3-5]. Several efforts have been made to use inelastically scattered electrons to form an incoherent imaging mode [3-5]. However, low-loss electrons still have a significant partial coherence and core loss electrons have extremely low intensity, which leads to a poor signal to noise ratio.

In this work, we set up an electron confocal imaging mode for 3D imaging using selected coherent elastically scattered electrons which are depth sensitive. As illustrated in Figure 1, if a sample is moved away from the confocal plane, a real space diffraction pattern will arise at the confocal plane. This diffraction pattern is a convolution of the original probe with the Fourier transform of the scattering potential, so it is a mix of both real and reciprocal space information. In particular, the separation of the diffraction beams is related to the distance z from the confocal plane to the object. We establish an experimental configuration to select preferentially these depth sensitive diffracted beams to obtain images that derive from 2D slices of the specimen. By moving the sample along the optic axis and taking successive images, the optical sectioning effect of can be achieved.

The experimental results of this diffraction confocal imaging mode are demonstrated in figure 2 using a double-aberration corrected Titan[3] 80-300 TEM/STEM. The sample is a thin carbon film with small random oriented gold nanoparticles distributed on the surface. The thin film is titled to ~ 15 degrees and images recorded in sequence as the sample is moved along the optical axis with a piezo stage. At each specimen position, depth-sensitive parts of the scattered intensity distribution in the confocal plane are selected and refocused onto a small STEM detector. For comparison, a through focus series of conventional HAADF-STEM images are also recorded. In the diffraction confocal imaging mode (Figure 2a and b), only a thin band of the sample at the chosen height of the confocal plane gives intensity in the image, clearly showing the optical sectioning effect. This compares favourably with the corresponding through focus series of HAADF-STEM images that show little depth dependent contrast at different focal planes. The reconstructed 3D images for SCEM and HAADF-STEM are compared in figure 2c and e. The SCEM correctly reconstructed a tilted thin film while the HAADF-STEM has limited depth resolution [6].

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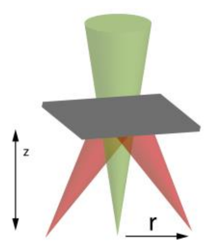

Figure 1. Illustration of real space coherent SCEM. The diffraction beam with momentum changes contains the depth resolution as the separation r is linked to the distance z.

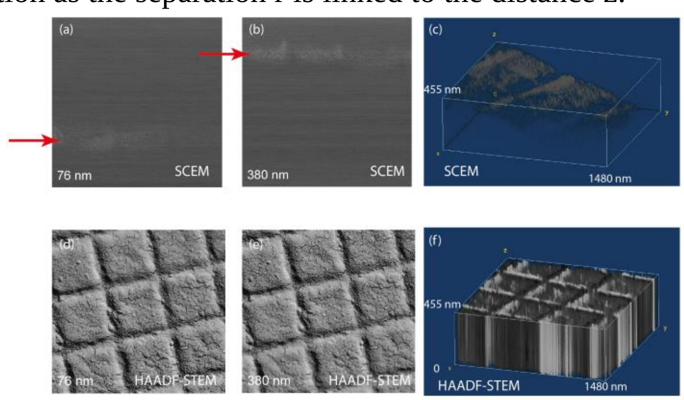

Figure 2. Experimental coherent SCEM images (a and b) and conventional HAADF-STEM images (d and e) of a tilted gold/carbon thin film focused at different height. The nominated focused heights are marked on the images (76 nm and 380 mm, respectively). The corresponding reconstructed images are compared in fig.2c and f.

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