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Improvement of TEM Spatial Resolution at Low Accelerating Voltages (15 - 30 kV) with Monochromator

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Development of transmission electron microscope at accelerating voltage lower than 60 kV is important for observing carbon related materials with low irradiation damage. The geometrical aberration corrector is a mandatory tool, especially for microscopy at low accelerating voltage, because the scattered electrons up to higher angle must be included in the formation of a high spatial resolution image. We have already developed the higher-order geometrical aberration corrector (Delta corrector) which can correct up to fifth-order aberrations including six-fold astigmatism. In a STEM ADF image at 30 kV, C-C dumbbells of graphene with a separation of 0.14 nm were resolved by the corrector with cold-field emission gun (CFEG) [1]. However, the C-C dumbbells cannot be resolved in TEM images with the Delta corrector and a CFEG. This is due to chromatic aberration; the resolution reduction by chromatic aberration in TEM is severer than that in STEM.

To achieve atomic resolution in low accelerating voltages, one of two ways must overcome. One is to correct chromatic aberration by a chromatic aberration (Cc) corrector [2], or to reduce energy spread of electrons. In the present study, we explore the TEM resolution using a monochromator dedicated for low accelerating voltages. The monochromator consists of two Wien filters [3]. The energy width can be selectable by changing a width of an energy slit. The monochromator is attached to a newly developed aberration corrected TEM equipped with the Delta correctors.

Figure 1 shows diffractogram tableaux at 30 kV used for the measurement of aberration coefficients of image forming lenses. In each of the diffractgrams obtained with a non-monochromated electron source (700 meV), the intensity of diffractogram is attenuated along radial direction due to the defocus spread in Fig. 1(a). On the other hand, in each of diffractgrams with a monochromated source (50 meV) is relatively isotropic due to small defocus spread in Fig. 1(b). The isotropic intensity indicates that the electrons scattered to higher angles do not blur TEM images. Thus, information limit of the image is definitely improved with use of the monochromated source.

Figure 2 shows TEM images of gold nano-particles on a carbon thin-film at 30 kV and their power spectra of the Fourier transforms under the illuminations from non-monochromated and the monochromated source. With the non-monochromated source, lattice fringes and diffraction spots of gold particles are barely visible in the image and the power spectrum, respectively. On the other hand, with the monochromated source, atomic columns of the particles and spots corresponding to $(0.09\ \mathrm{nm})^{-1}$ are clearly detected. These experimental observations demonstrated that the resolution of TEM images was drastically improved by reducing the energy spread of the electron source.

The images of gold nano-particles showed the resolution improvement. However, it is difficult to evaluate the resolution quantitatively because it includes non-linear contrast, which is enhanced by multiple scattering of electrons. Therefore, we examine to use a mono-layered specimen: mono-layered graphene to confirm the resolution improvement in linear component. In the TEM images of graphene taken at 60 kV (not shown here please see [4]) and 30 kV (Fig. 3(a)), the dumbbells with the separation of 0.14 nm are clearly resolved. The image of graphene at 15 kV shown in Fig.3(b) also shows the resolution improvement by the monochromator. In summary, we have demonstrated the drastic improvement of the spatial resolution in TEM by reducing the energy spread of the electron source with a monochromator at low acceleration voltages of 15 kV-30 kV [5].

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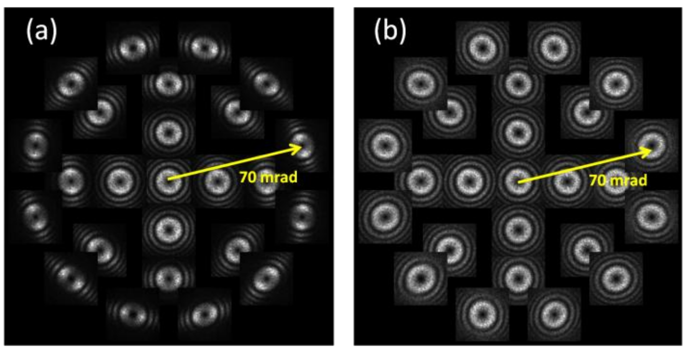

Figure 1. Diffractogram tableaux with (a) non-monochromated source and (b) monochromated source at 30 kV. The maximum beam tilt in the tableaux was 70 mrad and defocus was around -150 nm.

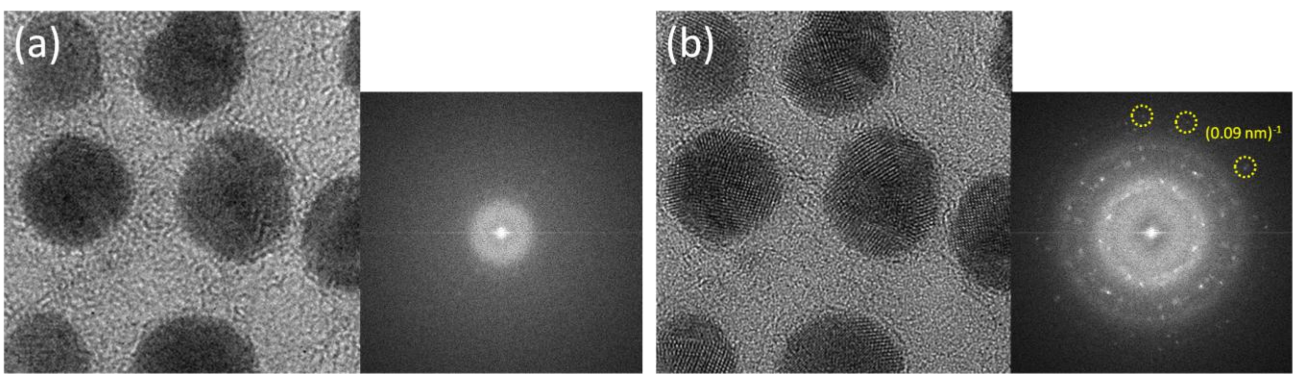

Figure 2. TEM images of gold nano-particles and their power spectrum of the Fourier transform at 30 kV with (a) non-monochromated source (700 meV) and (b) monochromated source (50 meV).

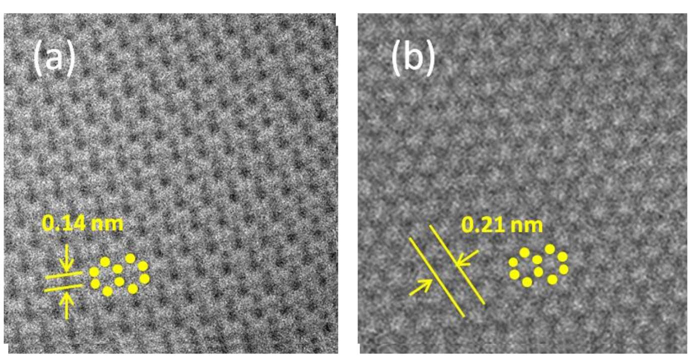

Figure 3. TEM images of graphene at (a) 30 kV and (b) 15 kV with monochromated source.

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