

## Low-Voltage TEM/STEM for Imaging and Spectroscopy of Low-Dimensional Materials

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Aberration correction is quite useful for low-voltage transmission electron microscopy (TEM/STEM) since the inferior spatial resolution due to longer wavelength of incident electrons can be compensated. Under the 3C project we have first developed a new Cs corrector (DELTA-type), which enables us to correct the geometrical aberrations up to the 5th order and the flat phase area is as large as 71 mrad after the 6 fold astigmatism is removed. A JEOL 2100F based STEM equipped with the DELTA corrector realize the 0.1 nm resolution even at the acceleration voltage of 30kV and the STEM spatial resolution ( $d$ ) can be estimated as  $d = 15.3\lambda$  [1]. After the geometrical aberration correction, other factors become important for further development of low-voltage TEM/STEM. Here in this presentation we will show our recent efforts to improve the performance of low-voltage TEM/STEM besides the higher-order geometrical aberration correction.

The chromatic aberration becomes an issue to limit the spatial resolution after the geometrical aberration correction. We then attempted to post-fit a newly designed Cc aberration corrector for image lens of our low-voltage TEM because. The chromatic aberration was successfully corrected for the TEM together with the higher geometrical aberrations [2]. Even though the Cc and Cs were both corrected, the performance of the low-voltage TEM did not show outstanding improvements most probably due to the intrinsic instabilities of the Cc corrector. Alternatively we have mounted a double Wien-filter type monochromator with a schottky source for our TEM/STEM. The monochromated TEM/STEM shows an excellent performance even at low-voltages. The spatial resolution of TEM has been magnificently improved by narrowing the energy slit to reduce the damping effect of the CTF envelope [3] (Fig.1). Also a CMOS based detector seems to be very much efficient to prove its high performance. Apart from the TEM resolution enhancement the monochromated EELS is also very helpful to perform optical spectroscopy in STEM mode though an atomic-size probe is not really needed for spectroscopy but for imaging only. The EELS signal delocalization at low-loss region is quite huge and the size of exitons would be not smaller than a few nanometers [4, 5, 6].

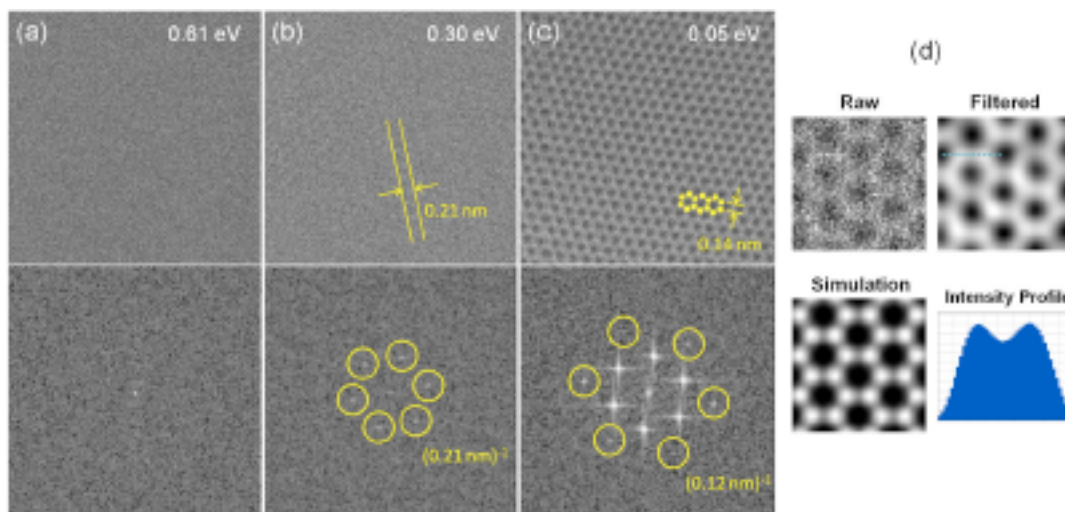
Such low-voltage TEM/STEMs will be very useful to investigate structures of low-dimensional materials without any thickness. Single atom imaging and spectroscopy can be routinely done for individual dopant atoms or impurities [7, 9]. We will review in this presentation our applications to this field [8].

### References:

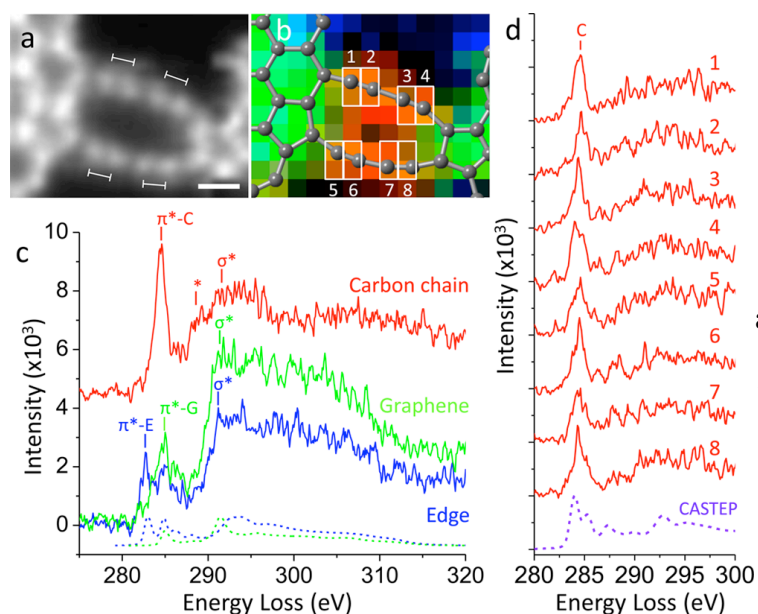
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**Figure 1.** 15kV TEM images of single layered graphene (Morishita *et al.*, in ref. [3]). Raw TEM images of monolayer graphene (top) and the power spectra of the Fourier transform of the images (bottom). The energy widths of the electron source are (a) 0.61, (b) 0.30, and (c) 0.05 eV. (d) Magnified graphene image with an energy spread of 0.05 eV. The low-pass filtered image was produced using the convolution of the Gaussian function ( $\sigma \approx 0.04$  nm). The intensity profile along the dotted line in the filtered image is also shown. The simulation image was calculated with a Cc of 0.6 mm and a defocus of 1.0 nm.



**Figure 2.** Atom-by-atom EELS from carbon atomic chain (YC Lin *et al.*, in ref. [7]) (a) ADF image of two parallel carbon chains. Scale bar is 2 Å. (b) The corresponding EELS color mapping overlapped with extracted atomic model. (c) Spectra shown are extracted from the sum of 10 pixels from the EELS map shown in (b). The simulated EEL spectra of graphene and edge are presented by green and blue dashed lines, respectively. (d) Atom-by-atom EEL spectra corresponding to each atom in the carbon chain.