Darkfield, Brightfield, and Energy-Filtered Nanotube Image Profiles

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Anyone who has been asked to examine carbon nanotubes in the TEM knows that cylindrical symmetry can be a wonderful thing. For example, if you would like to know how many graphene or BN sheets make up a given tube, or whether or not the tube has internal terminations, one image may do the job. In this paper, we discuss projected thickness and diffraction functions that provide a baseline for examining a variety of intensity profiles across nanotube images. These likewise assume that to first order the tube is cylindrically symmetric, the beam encounters the tube perpendicular to its symmetry axis, and that the contrast mechanisms are simple. One can always explore deviations from these assumptions after the fact.

First, consider darkfield images of a nanotube using the tube layering (e.g. graphite (002)) reflection. As a function of projected radial distance from the tube center, geometry shows this diffraction thickness, *d*, to be $\sim 2r\tan[\alpha]$, where α is the fringe visibility half angle for the layer spacing, provided the diffracting region is not being truncated by the outer or inner nanotube radii [1]. One use for this function is illustrated in the (002) darkfield image of a coated multi-wall carbon nanotube (perhaps 100 nm diameter) of Fig. 1. The upper right inset shows that indeed this linear ramp as a function of *r* nicely matches the contrast of the inner portion of both tubes in the image. More quantitative analysis might allow one to determine tube ID and amorphous rim thickness as well.

Secondly, consider the projected thickness, *t*, of a nanotube of outside radius r_{max} and inside radius r_{min}. This looks like $\sqrt{r_{max}^2 - r^2}$ for $r > r_{min}$, from which you subtract $\sqrt{r_{min}^2 - r^2}$ for smaller *r*. This function has a jump ratio $t[r_{min}] / t[0]$, which for a given r_{max} goes up rapidly in discrete steps to a maximum for single walled tubes like that shown in Fig. 2. This feature has been helpful in identifying portions of single walled tubes whose outer edges are obscured, although it should be carefully compared to defocus simulations for more quantitative work.

Lastly, application for the diffraction and thickness functions above also arises in the study of inelastic mean-free-path images. Mean-free-path “thickness” images can be calculated using the ratios of brightfield and elastic images taken with an energy-filtered TEM [2]. To explore effects of (002) diffraction on inelastic mean-free-path, we profiled such "thickness" images of a bamboo nanotube in Fig. 3. The plot below compares the nominal thickness function in blue to experiment. The jump ratio should be sensitive to changes in mean free path, in the (002) diffracting regions profiled in red, and thus this type of analysis can put upper limits on the size of such effects.

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References:

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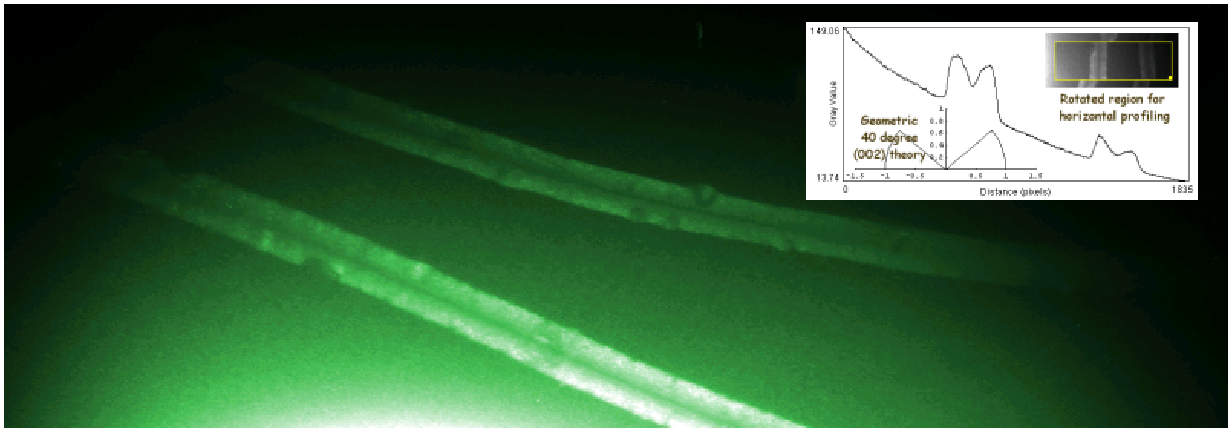

Fig. 1: (002) darkfield image of coated carbon nanotubes. The inset compares the intensity profile to the model.

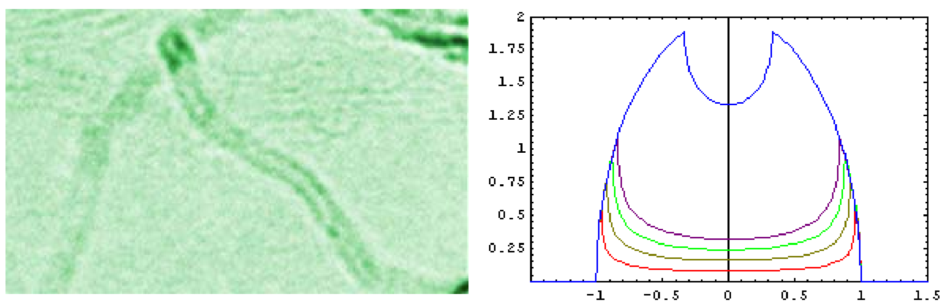

Fig. 2: Single-walled carbon nanotube brightfield image showing how the intensity between walls nearly returns to that of the adjacent hole. The accompanying figure illustrates the theoretical thickness profile for tubes of different inner and outer radii, where the red (lowest) curve is representative of single-walled.

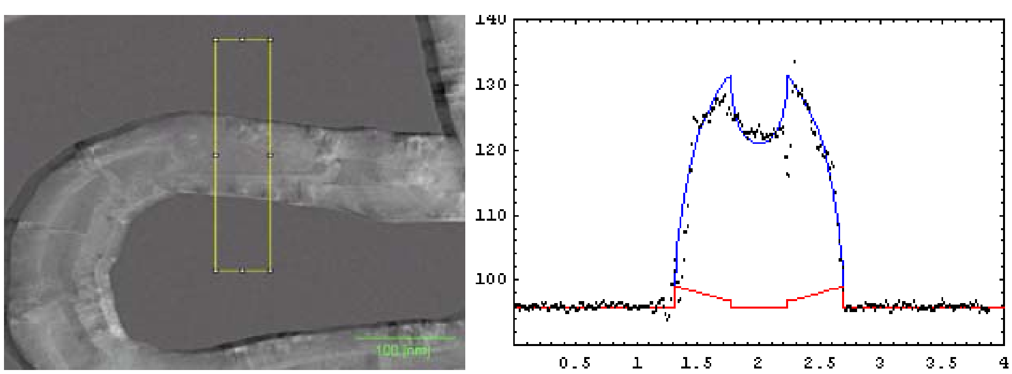

Fig. 3: A mean-free-path "thickness image" profiled against the thickness function (blue curve).