## Opinion

# When is Z-Contrast D-Contrast?

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The terms "Z-contrast" and "STEM imaging" have now become prevalent for any type of annular dark field (ADF) imaging in scanning transmission electron microscopy (STEM) instruments. This is a problem and one, which in the opinion of the authors, the electron microscopy community should start to pay attention to. The issue is both simple and subtle at the same time; often ADF images contain substantial diffraction contrast for various reasons ranging from orientation changes to effects such as dechanneling due to amorphous films or strain (see Figure 1 and [1–4]).

Why should this matter? We need to follow a simple logical train of thought. Suppose a non-expert (Joe the faculty) uses the term Z-contrast in a talk and provides simple interpretations of images provided to him by students who have not had a rigorous training in transmission electron microscopy. Some of these interpretations will be wrong; we suspect many readers have their own examples. Later someone else will investigate the same system more carefully and point out the error in the science described by Joe. Like all good faculty (we hope) Joe will not blame his students, so it must have been the microscope that gave erroneous results. Because Joe now knows that electron microscopy can give inaccurate results, Jennifer (in a different department) will learn of this, and the process cascades.

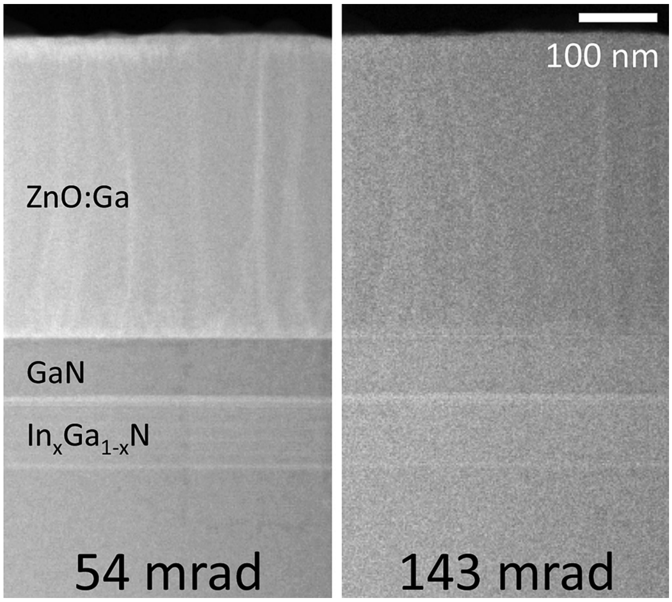


**Figure 1:** ADF STEM images of a Ga-doped ZnO thin film on a GaN layer that contains an $In_xGa_{1-x}N$ quantum well structure. Simple "Z" contrast predicts that the $In_xGa_{1-x}N$ should be brighter than the GaN, and the ZnO should be slightly less bright. In the left-hand image, acquired with an ADF inner angle of 54 mrad, the InGaN/GaN contrast is as expected, but the ZnO/GaN contrast is reversed. Within the ZnO, there is contrast from grain boundaries and small changes in the orientation of different crystal grains. Only when the detector angle is increased almost threefold to 143 mrad is the expected Z-contrast recovered, as shown in the right-hand image. The increase in detector angle results in a dramatic decrease in intensity. (Images are courtesy of Andrew Y. Yankovich and were acquired at 200 kV in a probe-corrected Titan STEM at a convergence angle of 24.5 mrad and resolution of ~0.1 nm. The ADF detector outer angle is 5 times the inner angle.)

Something similar occurred some years ago with high-resolution electron microscopy (HREM) in inorganic chemistry. Some journals were persuaded to insist that publications with any new oxide structure include an HREM image (ideally a focal series) and image simulations, ignoring the question of whether the imaging parameters were really correct against those listed by the manufacturers' advertisements and whether the thickness was enough for a self-sustaining sample. Indeed, the imaging parameters were often not reported at all [5]. After a while, it became clear that this was not really contributing much new science, so HREM became less common despite the fact that it is often needed to check for features that can be missed in X-ray diffraction structure solution methods, such as weak superstructures or twinning.

The same can be said currently about nanoparticles. Again, an HREM image, sometimes with inappropriate imaging parameters, thickness, or orientation has become de-rigueur.

What should we do? How can we encourage appropriate use of these terms? Two suggestions:

a) Manufacturers and microscopy practitioners should not use the term ADF "Z-contrast" or the horrible term "STEM image" unless they are really certain that the collection angles are large enough.
b) Until dynamical-diffraction correctors are developed, practitioners should stress the importance of a user interpretation corrector (sometimes called a Prof).

## References

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