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Improving the Spatial Resolution of Low-keV STEM with a Monochromator

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When aberration-corrected scanning transmission electron microscopy (STEM) is carried out at a low primary energy, the spatial resolution is typically determined by chromatic rather than geometric aberrations. Low keV STEM is desirable for a variety of reasons: knock-on radiation damage can be reduced or even eliminated; Cherenkov losses, which can pose a serious problem for band-gap determination using electron energy loss spectroscopy (EELS), become less problematic; and achieving good EELS energy resolution, whose difficulty scales inversely to $\partial E/E_o$ (where ∂E is the energy resolution and E_o the primary energy), becomes less demanding.

The chromatic resolution limit is proportional to $(\Delta E\ C_c)^{0.5}$, where ΔE is the energy spread of the primary beam and C_c the coefficient of chromatic aberration of the probe-forming optics [1]. Chromatic effects can therefore be reduced, and the resolution potentially improved, using two different approaches: by making the energy spread smaller, or by decreasing C_c. With the Nion monochromator [2-4], both approaches are possible.

The first approach is simple in principle. However, for a useful resolution improvement to be observed in practice, many things must be done right:

a) The electron source must be bright and energetically narrow enough so that a monochromated probe can have sufficient beam current without the source needing to be greatly magnified. At present, this requires an ultra-bright cold field emission gun (CFEG).

b) The energy-dispersed beam that is incident on the monochromator slit must be stabilized in energy to better than ~50 meV, to prevent the appearance of intensity streaks in scanned images.

c) Aberrations at the monochromator slit must be corrected to at least the 2nd and preferably 3rd order. In addition, charging of the slit and other potential beam-broadening effects must be avoided.

d) Energy-dispersion cancellation in the second half of the monochromator must be precise enough so that the probe is not appreciably broadened due to un-cancelled dispersion. In other words, the monochromator must not enlarge the source size; it must simply decrease the energy spread ΔE.

e) Geometric aberrations must be corrected more precisely than in the non-monochromatic case so that a larger probe angle can be used without the electron wavefront becoming unduly distorted.

The above conditions have recently been met. Figure 1 shows an ADF STEM image of Au nanoparticles taken at 60 keV with the Nion monochromator's slit selecting ΔE~100 meV, and a Fourier transform documenting transfer up to $(0.93\ \text{Å})^{-1}$ [Au (331)]. In the equivalent non-monochromated case, only $(1.2\ \text{Å})^{-1}$ was captured. To our knowledge, this is the first demonstration that the STEM spatial resolution can be improved by monochromating. It is worth noting that this approach cannot avoid a loss of beam intensity due to the energy selection at the slit, but that it improves the attainable EELS energy resolution, and reduces the tails of the zero loss peak [5].

For the second approach, we use a correction principle new to electron microscopy: two C_c-adjusting sextupoles that act on an energy-dispersed beam [2]. This approach has the advantage that there is no loss of beam current, since no energy-selecting slit is used.

Improving the chromatic resolution limit shifts the attention back to geometric aberrations, which once more become limiting, even at low primary energies. Improving the geometric aberration performance on a routine basis requires more flexible and precise control of parasitic aberrations, substantially improved system stabilities, and better diagnostic tools. We are making important progress on all three fronts, with newly improved parasitic aberration controls for the Nion C3/C5 aberration corrector [6], power supplies of increased stabilities and improved magnetic shielding of the column, and an improved Ronchigram CCD camera.

At the meeting, we will present a comparison of the two approaches, with a focus on primary energies lower than 60 keV, at which the resolution improvements promise to be especially major.

References:

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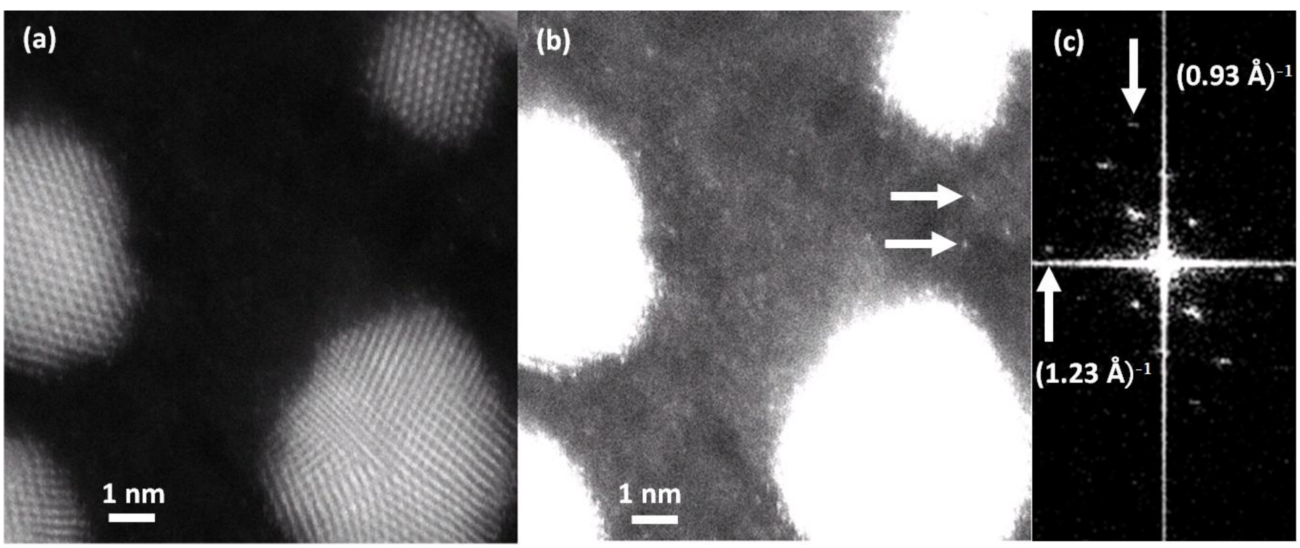

Figure 1. (a) 60 kV monochromated HAADF STEM image of Au nanoparticles on a carbon support, (b) same image, but with the contrast adjusted to show individual Au atoms, two of which are labeled with arrows. (c) FT of a particle in a similar image.

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