

Using a monochromator to improve the resolution in focal-series reconstructed TEM down to 0.5Å

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The resolution of present-day spherical-aberration corrected TEMs is limited by the chromatic aberration of the objective lens to about 0.7Å at 300kV. The resolution can be improved by Cc correction or by reducing the energy spread in the illumination with a monochromator. We used TEAM 0.5, a special Titan column built within the TEAM project [1], and on this microscope we succeeded to improve the resolution to 0.5Å by monochromation, not only in single images but also in images reconstructed from focal series. Such reconstructed images are free of possible contrast reversals due to incorrect focusing and possible artifacts due to non-linear interferences. However, focal series are more demanding to acquire than single images because of the higher demand on the stability of the column, and because they must be taken over some focus interval and this significantly increases the demands on the parallelness or coherence of the beam.

The coherence of the beam is closely related to brightness of the source. In STEM, brightness determines how much beam current can be squeezed in a small probe for a given convergence angle. Similarly, in TEM, brightness determines how much beam current can be squeezed in a parallel beam for a given coherence angle.

We estimate that, in order to show 0.5Å in a focal series of a typical length of 40nm, the brightness *after monochromation* must be at least $\sim 3 \cdot 10^8$ A/cm²/sr. This is not easy to obtain because this brightness is comparable to what a standard Schottky FEG delivers at 300kV and 4kV extraction voltage *before monochromation* (the brightness after monochromation is at least a factor 3 to 10 lower than the brightness before monochromation because the monochromator removes part of the energy spectrum, and the source can be blurred by aberrations or Coulomb interactions in the monochromator). We used a prototype 'high brightness' gun (currently being developed within the TEAM project) and a monochromator designed for minimum brightness loss [2], and we obtained an exceptionally high brightness $> 5 \cdot 10^8$ A/cm²/sr at $\Delta E = 0.13$ eV.

In our set-up, the source was focused on the specimen to a probe of about 100nm diameter and 0.1mrad convergence angle, and this probe was dispersed by the monochromator to a line of about 1μm length, as shown in Figure 1. In this way, the non-roundness of the dispersed probe is only present in the specimen plane, and not in the reciprocal plane. This ensures that the power spectra of the images are round, not only close to focus but also at the end of the focal series, as demonstrated in Figure 2. Figure 3 shows an example of an exit wave reconstructed from a focal-series of 30 steps at 0.9nm focus intervals. The Fourier Transform of its phase shows information down to 0.5Å. [3].

1. <http://ncem.lbl.gov/TEAM-project/>
2. P.C. Tiemeijer, Ultramicroscopy **78** (1999), p. 53.
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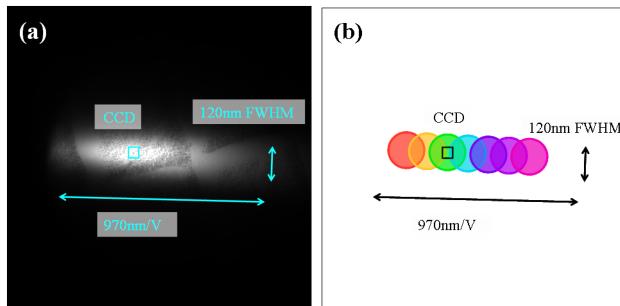


Figure 1. The dispersed probe is focused on the specimen. In this example, the convergence was $\alpha=0.09\text{mrad RMS}$ and $J=20\text{A/cm}^2$ on the area sampled by the CCD.

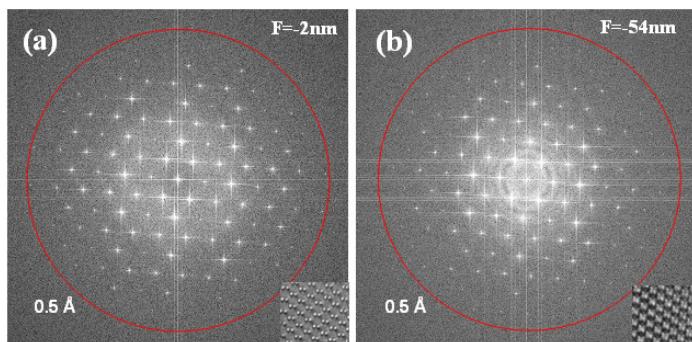


Figure 2. Fourier transform of images of Ge<110>. Settings: $\Delta E=0.13\text{eV}$, $J=40\text{A/cm}^2$, $\alpha=0.13\text{mrad RMS}$, 1s exposure. (a) 2nm underfocus, (b) 54nm underfocus.

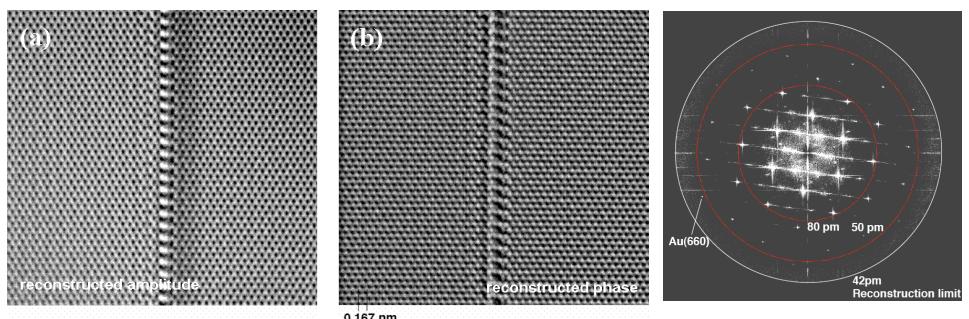


Figure 3. Focal-series reconstruction of a grain boundary in Au<111> ($\Delta E=0.13\text{eV}$, $J=90\text{A/cm}^2$, $\alpha=0.18\text{mrad RMS}$, 1s exposure). (a) Amplitude, (b) phase, (c) FT of phase.