Improvement of Spatial Resolution of STEM-HAADF Image by Maximum-Entropy and Richardson-Lucy Deconvolution

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Images obtained by using a high-angle annular dark-field (HAADF) detector in the scanning transmission electron microscope (STEM) are able to resolve atomic columns of crystalline materials [1]. This imaging is believed to be incoherent and described as a convolution of a scattering distribution and an electron probe [2]. Therefore, any deconvolution techniques may improve image resolution by eliminating a broadening caused by the electron probe. Maximum entropy method (MaxEnt) [3] was adapted and tested on STEM-HAADF images from Si<110> and GaAs <110> [4]. Richardson-Lucy algorithm is another promising deconvolution technique [5], which has been successfully applied to correct a defect of Hubble space telescope images. In the field of electron microscopy, this technique was applied to EELS [6] and CBED [7]. Here, we report improvement of spatial resolution of STEM-HAADF images by deconvolution procedures developed on the same principles to improve energy resolution of EELS (DeConvEELS) [8] using maximum entropy (ME) based on Collin's approach [9] as well as Richardson-Lucy (RL).

Both algorithms are based on Bayes' theorem of probability to reconstruct the most probable image, which is consistent with the observed data. The procedures do not perform a direct deconvolution, but estimate a predicted image by convoluting it with the probe function. Therefore, they are not so much affected by noise compared with the Fourier deconvolution. It is interesting to note that these deconvolution routine can eliminate also an artificial convolution applied to reduce the noise in the image, which is not possible by using the Fourier deconvolution. Since both procedures iteratively estimate the most probable image, important issues are how to control their convergence and when we stop the processing. Therefore, there are a few parameters for these procedures that may be optimized for each image to be processed. However, it may be worthwhile to note that the following results were obtained by using default parameters.

Figure 1 show an original image and its Fourier transform. The original image was taken from a quasi-crystal AlNiCo (low-temperature phase with superlattice-structure) using JEOL 2010F [10] (200 kV, Cs: 0.5 mm, probe forming angle: ~12 mrad, ADF detector: 60 – ~110 mrad.). The Fourier transform shows spots up to 8.0 /nm (resolution of 0.125 nm). Figure 2 shows the results obtain by the ME deconvolution using a calculated probe assuming z = -45 nm, and its Fourier transform. Here, we can see spots extending up to 1.20 /nm (resolution of 0.083 nm), and quantum noise is greatly reduced. The RL deconvolution shows similar performances as reported here. In conclusion the deconvolution procedures (DeConvHAADF) [11] developed here can significantly improve resolution and at the same time greatly reduce noise even of a non-periodic image.

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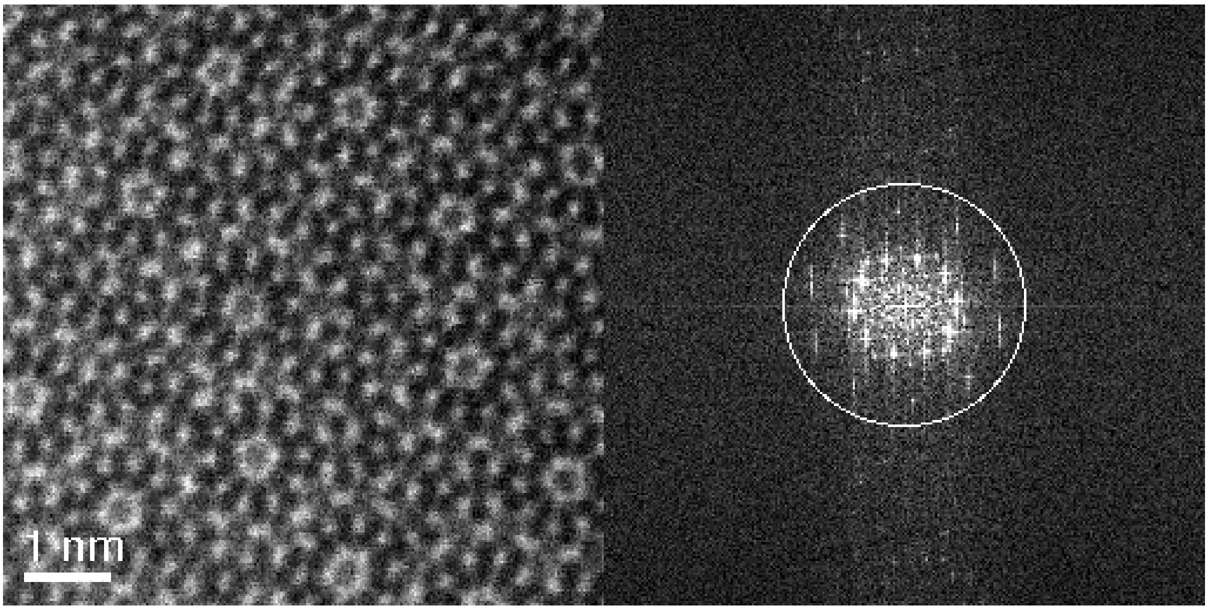

Figure 1. Original quasi-crystal image and its Fourier transform. The image was obtained by using JEOL 2010F (200 kV, Cs: 0.5 mm, probe forming angle: ~12 mrad, ADF detector: 50 – ~110 mrad.). The Fourier transform shows spots up to 8.0 /nm (a circle shown here).

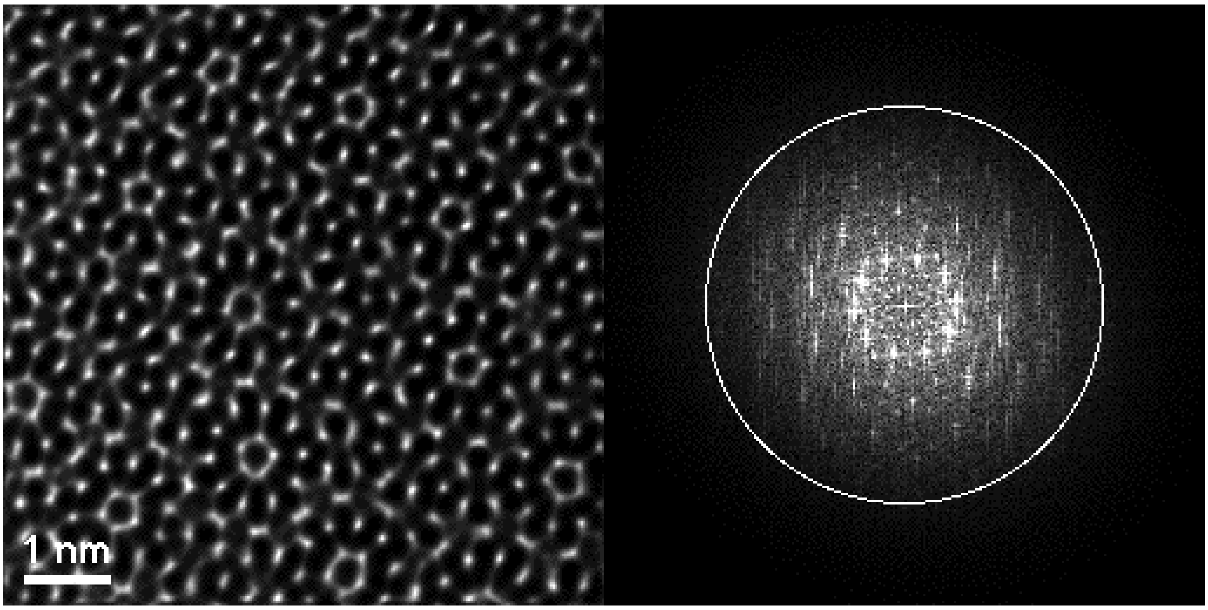

Figure 2. ME deconvolution using a calculated probe assuming z = -45 nm (at 64 cycles), and its Fourier transform. The Fourier transform shows spots up to 12.0 /nm (a circle shown here). Quantum noise is substantially reduced.