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Scanning distortion correction in STEM images

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ABSTRACT

Various disturbances do exist in the image taking process of scanning transmission electron microscopes (STEM), which seriously reduces the resolution and accuracy of STEM images. In this paper, a deep understanding of the scanning distortion influence on the real and reciprocal spaces of STEM images is achieved via theoretical modeling and simulation. A scanning distortion correction algorithm is further developed based on two images scanned along perpendicular directions, which is able to effectively correct scanning distortion induced deviations and significantly increase the signal to noise ratio of STEM images.

1. Introduction

High angle annular dark field STEM (HAADF STEM) [1] and annular bright field STEM (ABF STEM) [2] images provide intuitively structural and compositional information of materials at the atomic scale, especially when the microscope is equipped with a spherical aberration corrector [3,4], cold field emission gun [5] and monochromator [6]. However, the accuracy and resolution of the acquired STEM images are seriously limited by environmental disturbances such as electromagnetic interference, mechanical vibration, instability in power supply, and other factors [7]. Accordingly, great efforts have been made to correct scanning distortion in STEM images. For example, Sanchez et al. [8] developed an algorithm by applying the strain mapping techniques to STEM images in order to provide a broad analysis of the systematic scanning distortion, which was based on the assumption that the distortion was the same for every image at a given magnification (i.e., ‘systematic’). Braidy et al. [9] proposed a method to analyze and correct the systematic scanning distortion induced shifts containing horizontal and vertical displacement in pixel rows of STEM images. Ophus et al. [10] designed a procedure to correct linear and nonlinear distortion of STEM images from image pairs with orthogonal scanning directions, in which the images along the fast scanning direction was assumed to have negligible errors. Zuo et al. [11] also developed a quantitative lattice analysis and scanning distortion correction approach for STEM images based on the image processing technique of template matching. Sang et al. [12] introduced the “revolving STEM” method, which enables STEM image distortion to be characterized and removed by using a series of fast-acquisition STEM images with rotated scan coordinates. Jones et al. [13] succeeded in the distortion correction of atom resolved STEM images by a restoration of atom features and then compensation of scanning distortion induced drifts, in which the drift rate and direction during the time of the STEM probing process were assumed to be constant. Rečnik et al. [14] successfully used conventional TEM (CTEM) images as references to correct the corresponding STEM images. Based on non-rigid registration and averaging of an image series of short–exposure STEM images. Yankovich et al. [15] et al. successfully developed a scheme to achieve extremely high signal to noise ratio (SNR) images, with which atom column positions could be measured with a sub-picometre precision.

Although great progress has been achieved in scanning distortion correction of STEM images, there are still many challenging scanning distortion features to be further investigated. For example, Fig. 1(a_1) and (b_1) are two HAADF STEM images of a gold nanoparticle taken with the same electron microscope at different times; Fig. 1(c_1) is a HAADF STEM image of another gold nanoparticle; and Fig. 1(a_2), (b_2) and (c_2) are the corresponding Fourier transformed patterns (power spectrum) of the HAADF STEM im-

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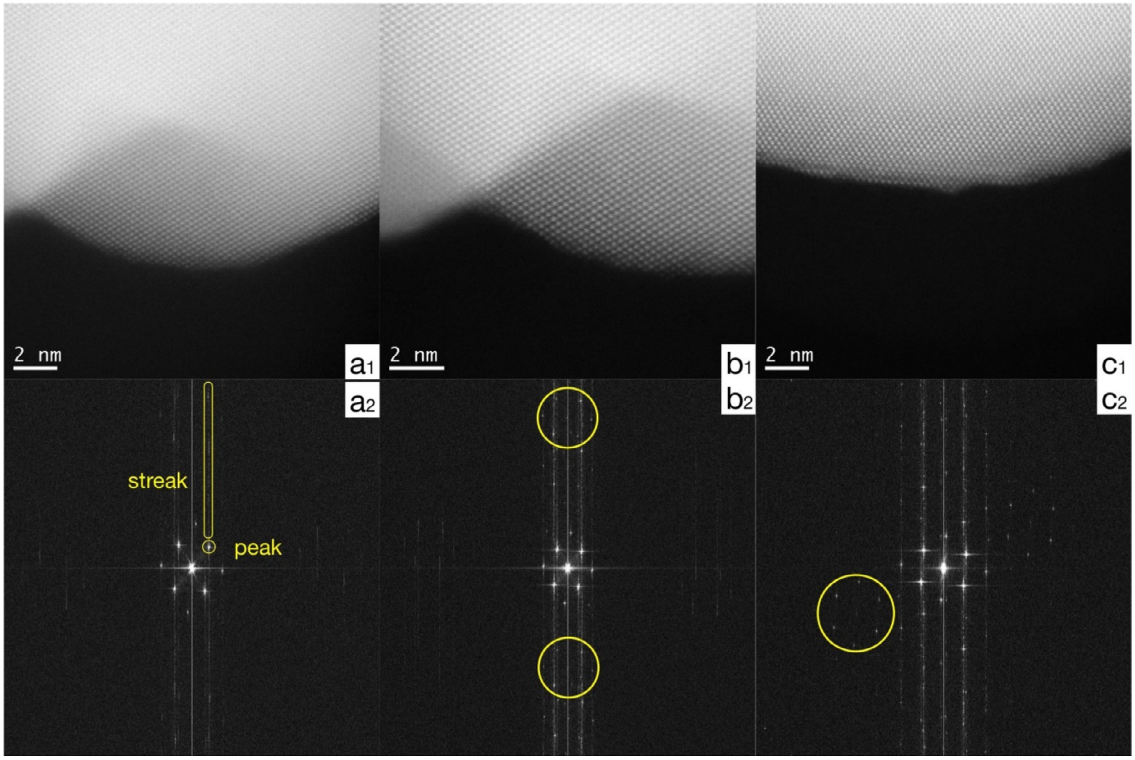

Fig. 1. (**a**$_1$) and (**b**$_1$) are HAADF STEM images of a gold nanoparticle along [110] zone axis taken at different times. (**a**$_2$) and (**b**$_2$) are the Fourier transformed patterns (power spectrums) of (**a**$_1$) and (**b**$_1$), respectively, where the vertical light points and lines are called peaks and streaks, respectively, as exampled by the peak inside two yellow circles in (**b**$_2$) and the streak inside a yellow loop in (**a**$_2$). Comparing (**b**$_2$) to (**a**$_2$) indicates on-streak pseudo peaks in (**b**$_2$). (**c**$_1$) and (**c**$_2$) are a HAADF STEM image of another gold nanoparticle along [110] zone axis and its Fourier transformed pattern, respectively, where off-streak pseudo peaks appear in (**c**$_2$). Pseudo peaks and streaks are caused by scanning distortion during taking HAADF STEM images, thereby indicating that the images are deviated at certain degree from the corresponding ideal ones.

ages. As indicated in Fig. 1(a$_2$), the bright points are called peaks and the vertical lines running through the power spectrum and in pairs with peaks are called streaks [8]. However, some bright points far away from center, called pseudo peaks here, also appear in the power spectrums, as shown in Fig. 1(b$_2$) and (c$_2$). The on-streak pseudo peaks in Fig. 1(b$_2$) and off-streak pseudo peaks in Fig. 1(c$_2$) are caused by scanning distortion and will be explained later. Obviously, novel methods to correct the scanning distortion influence in STEM images are urgently needed in order to improve the image quality.

In this work, the influence of scanning distortion on STEM images is fully analyzed in both real and reciprocal spaces by modeling and direct simulations. A scanning distortion correction algorithm, which results in reliable coordinates of projected atom column positions in the 2D images, is developed based on two images scanned along two directions perpendicular to each other.

2. Materials and methods

2.1. Scanning distortion modeling and analysis

Fig. 2(a) schematically shows the STEM working principle. Controlled by the scanning coils, the electron probe scans an area in physical space pixel by pixel with a constant stationary probing time on each pixel, hereafter the probing time is called the dwelling time. The collectors in a STEM collect the scattered electrons and the controlling system assigns the collected electron signals to corresponding pixels in the image plane. The dimension of each square shaped pixel in the physical space is determined by magnification. Here, the scanning direction is called the row direction and denoted by axis **a** as illustrated in Fig. 2(b). After scanning the first row of n pixels, the electron probe jumps back to the starting point in the column direction denoted by axis **b**, moves a pixel size below, and then scan n pixels of the second row. In this way, the electron probe scans the physical area pixel by pixel and row by row continuously. In this scanning mode, the row and column are clearly the fast and slow scanning directions, respectively. For a squared physical area, there are usually n rows and each row contains n pixels, thus there are $n \times n$ pixels in the generated image. The time taken for the probe to move from a row's end pixel to the next row's beginning pixel is named as fly back time. If the fly back time is sufficiently small, the time consumed to take a STEM image is approximately estimated by the product of dwelling time and total pixel number. As an example, Fig. 2(c) and (d) show the perfect mapping from the physical space to the STEM image without any scanning distortion, where the aqua blue boxes with 9.49 pm interval indicate the positions of the electron probe imposed on the sample. The scanning begins at the left-top corner in the physical space, corresponding to the left-top pixel in the image, and moves from left to right horizontally, called 0-degree scanning. The pixel to pixel mapping relationship between the physical and image space is illustrated by the red lines between the magnified parts, as shown in Fig. 2(c) and (d).

Scanning distortion causes offsets in projected atom column positions between a real image with distortion and its corresponding prefect image without distortion. As a special case, Fig. 3(a) and (b) show the simple scanning distortion, called flags and skips [8], where the scanning distortion induced displacement in an individual pixel row is a constant vector, although the magnitude and direction of the vector may change from row to row. A Cartesian coordinate on an image plane is established based on the **a** and **b** axes (Fig. 2(b)). The intensity distribution of an STEM image is a function of a and b, where a and b are integers considering the discrete nature of pixels in the units of pixel size, i.e., the pixel size