1865
doi:10.1017/S1431927615010107 Paper No. 0931
Microsc. Microanal. 21 (Suppl 3), 2015

Resolution Assessment of an Aberration Corrected 1.2-MV Field Emission Transmission Electron Microscope

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Observations of the structure and electromagnetic field at atomic resolution are critical for developing advanced materials. A lot of efforts are being made for achieving atomic resolution and for constantly improving it in transmission electron microscopes (TEMs) not only at the conventional in-lens specimen position (HR position) but also at a field-free specimen position (Lorentz position). In the last decade, $1/0.05\ nm^{-1}$ information transfer for 300-kV TEM has been demonstrated [1], and 0.5-nm resolution in Lorentz microscopy has been reported [2,3]. We developed an atomic-resolution holography electron microscope (1.2-MV TEM) equipped with a cold field-emission gun and a CEOS hexapole Cs-corrector. In this paper, we report on the resolution assessment of the developed 1.2-MV TEM. We found that the resolution reached 0.043 nm at the HR position and 0.24 nm at the Lorentz position.

Our strategy to define the instrumental resolution of the 1.2-MV TEM was to measure the maximum spatial frequencies both of a linear information transfer and of a no-reversal contrast transfer. If the maximum spatial frequency with no contrast reversal attained by the Cs-corrector was substantially higher than the linear information limit, we could state the instrumental resolution reached the information limit. Imaging resolution can also be checked by visualizing images of separated atomic columns or structures, which are restricted not only by the instrumental resolution but also by the beam-specimen interactions and the signal-to-noise ratio due to the total electron dose.

For the HR position, a linear information transfer was verified using a chromatic lattice image [4]. Diffraction spots of 000, and 633, 642, 651 of <111>-oriented W produced under axial illumination were selected using two holes fabricated on a Cu plate situated at an objective aperture and then were interfered each other at an image plane. If lattice fringes are visualized, a linear information transfer with corresponding fringe spacing can be verified. Figures 1(a) and (b) show the chromatic lattice image of W and its Fourier transform (FT). Since W{633} fringes and the corresponding reflection spots were clearly visible, a 0.043-nm linear information transfer was confirmed. A two-dimensional coherent phase contrast transfer function (PCTF) depicted by using the residual aberrations showed no contrast reversal up to a spatial frequency of $1/0.034\ nm^{-1}$. Both measurements enable us to conclude that the 1.2-MV TEM has 0.043-nm instrumental resolution.

Imaging of 0.044 nm-separated dumbbells of <411>-oriented GaN was demonstrated. Approximately 3 nm-thick areas near a cleaved edge of GaN were observed because the exit wave no longer has a separated structure at the thick area due to beam broadening in the sample. Film was used for recording. The total dose was approximately $2x10^6\ e^-/nm^2$. Figure 2 shows (a) observed Ga dumbbells with 0.044 nm separation and (b) a simulated GaN image with the signal-to-noise ratio (SNR) that stems from the finite electron dose and the detection efficiency.

For a field-free observation, the 1.2-MV TEM implements a dedicated imaging lens (Lorentz lens) above a conventional objective lens and an additional specimen stage (Lorentz position). The linear information transfer for the Lorentz position was examined by Thon ring patterns appearing in the Fourier transform (FT) of the image of amorphous carbon (10 nm) with Au particles (Fig. 3(a)). Images were taken by a CCD camera with a Nyquist frequency of 20 nm^{-1}. The radial line profile of the Thon ring showed a 1/0.24 nm^{-1} linear information transfer (Fig. 3(b)). 111-reflections (1/0.235 nm^{-1}) are also visible. A two-dimensional CTF estimated by the residual aberrations for the Lorentz position showed no contrast reversal up to a spatial frequency of 1/0.19 nm^{-1}. Hence, the instrumental resolution at the field-free specimen position was concluded to reach 0.24 nm. We were also found that images of the {111} lattice with 0.235 nm spacing in polycrystalline Au particles could be obtained with a total dose of about 1×10^6 e^-/nm^2 (Fig. 3(c)).

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[5] This research was supported by a grant from the Japan Society for the Promotion of Science (JSPS) through the “Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program)” initiated by the Council for Science and Technology Policy (CSTP). We thank Dr. M. Haider, Dr. H. Müllar, and CEOS GmbH for developing the Cs-corrector.

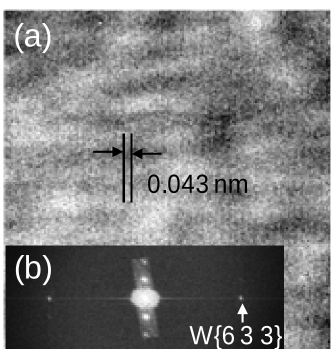

Figure 1. (a): Chromatic lattice fringes of tungsten at HR position. (b): FT of (a).

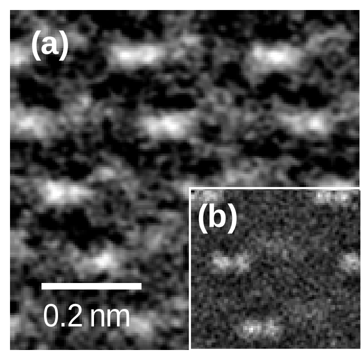

Figure 2. (a): Observed 0.044-nm GaN dumbbells. (b): Simulated image with SNR on electron dose.

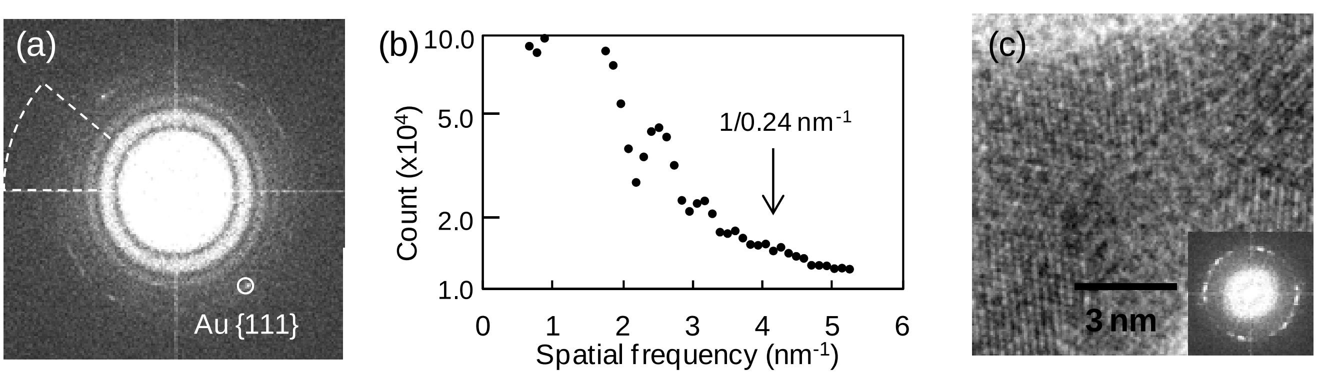

Figure 3. (a):Diffractogram of amorphous carbon with Au particles taken at Lorentz position, (b): Radial line profile at a sector in (a), (c): Image of Au {111} lattices with 0.235 nm spacing.