Effect of dynamical diffraction on phase shift in electron holography study

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With recent improvements in the precision and sensitivity of electron holography, the effect of dynamical electron diffraction on the phase shift has become important [1-3]. In the present study, holograms were recorded from a wedge-shaped transmission electron microscopy (TEM) specimen of single-crystal Si under a Bragg diffraction condition, and the phase shift was analyzed using dynamical electron diffraction theory (Bethe method).

The TEM specimen was prepared from a Si(100) wafer using a focused ion beam milling system (JIB-45000 MultiBeam, JEOL). The wedge angle was about 52°. Electron holography was performed using a 300 kV TEM system (JEM-3000F, JEOL) equipped with a single biprism. The holograms were recorded under a two-beam condition (transmitted beam and 220 reflection). The incident beam direction was controlled using the beam tilt function. To simulate the intensity and phase shift of the transmitted beam, nine beams in a 220 systematic row were considered in the calculations.

Figure 1 shows bright-field images, reconstructed phase images, and phase-shift profiles under a non-Bragg condition and a 220 Bragg diffraction condition. Under the non-Bragg diffraction condition, the phase shift increases in proportion to specimen thickness. On the other hand, under a 220 Bragg diffraction condition, the phase shift jumps by 180° where the dark thickness fringes appear in the corresponding bright-field image.

Figure 2 shows the calculated results for the thickness dependence of the intensity and the phase shift. In the graphs in the center column, the specimen is under an exact 220 Bragg diffraction condition, and the 180° jump in the phase shift at the dark thickness fringe positions is again seen. The left and right columns show the results when the sign of the excitation error for the 220 reflection is negative and positive, respectively. Although from the intensity profiles, thickness fringes are clearly present, the intensity of the dark fringes does not become zero, and there are no jumps in the phase-shift profile. It is considered that these jumps only occur when the intensity becomes zero, because the intensity is the sum of the square of the real and imaginary components of the complex wavefunction. It should be noted that the gradient of the phase-shift curve depends on the sign of the excitation error. This was also confirmed experimentally from a series of reconstructed phase images obtained for different incident beam directions. These experimental results can be explained qualitatively based on the Howie - Whelan - Darwin equations for the two-beam approximation. Near the Bragg condition, two Bloch waves with slightly different wavelengths are excited, and the excitation rate depends on the incident beam direction.

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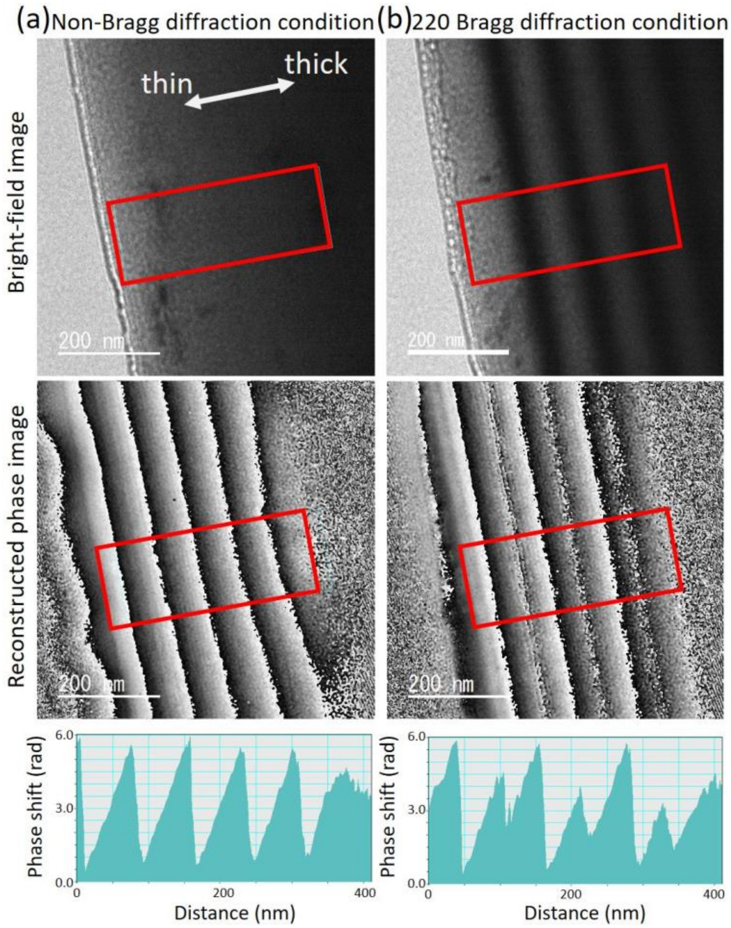

Fig. 1 Bright-field images, reconstructed phase images, and phase-shift profiles for wedge-shaped single-crystal Si specimen.

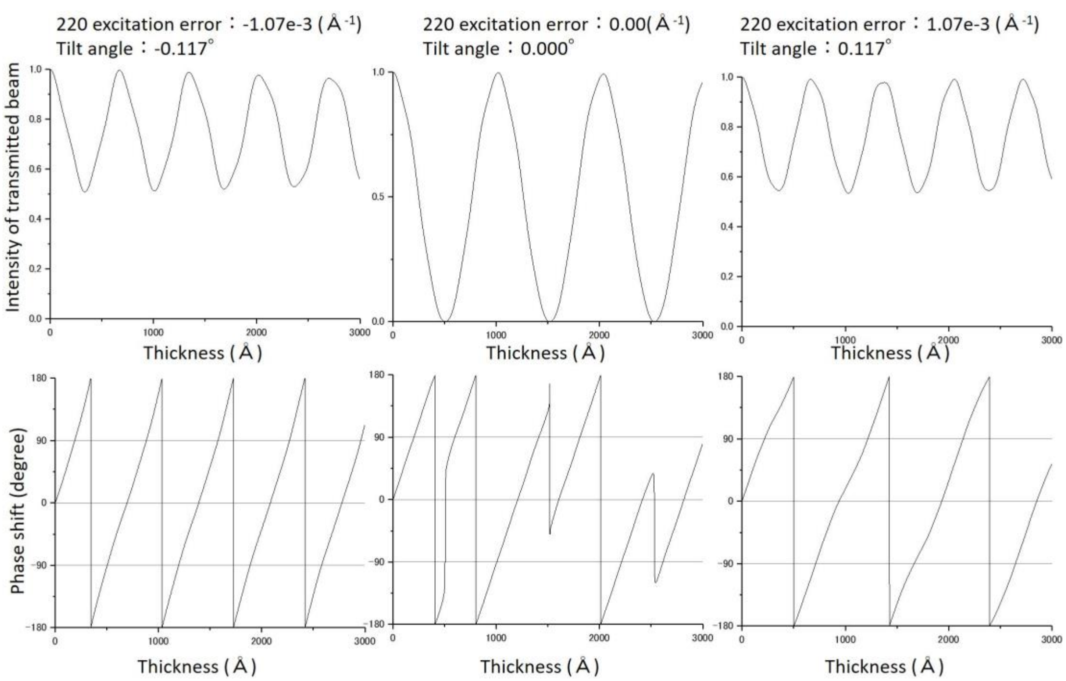

Fig. 2 Transmitted beam intensity and phase shift calculated using dynamical electron diffraction theory.