Achieving High-Resolution Electron Nano-crystallography using HVEM and PED

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Background
To achieve higher resolution in TEM, a Cs corrector is typically employed as a hardware solution. Alternatively, software processing techniques like Maximum-likelihood (MAL), Exit-wave function reconstruction (EWFR), Iterative wave-function reconstruction (IWFR), and Phase extension offer an affordable solution without requiring expensive hardware. However, these methods necessitate acquiring multiple HREM images (3-20) for processing. HVEMs are beneficial for HREM due to their deeper sample penetration and reduced dynamical effects. PED further minimizes dynamical effects, enabling high-resolution diffraction data even for thicker samples analyzed with lower-voltage TEMs. This study employed a combined approach of HVEM, PED, and phase extension to achieve sub-Ångstrom resolution imaging of Si single crystal samples. Additionally, we conducted a comparative analysis of the results with those obtained using a conventional TEM equipped with a monochromator and a Cs corrector.

Methods
A Si single crystal was prepared using ion thinning and employed as a test specimen for high-resolution electron microscopy (HREM). High-resolution electron microscopy (HREM) imaging of the Si [211] zone axis was performed using a high-voltage electron microscope (HVEM). The high-resolution images used for comparative analysis were obtained using a conventional TEM equipped with a monochromator and a Cs corrector at an accelerating voltage of 200kV. An energy-filtered precession electron diffraction (EF-PED) pattern was obtained using an energy-filtered TEM equipped with a precession unit. The specimen thickness was estimated using the log-ratio method and information from the low-loss spectra. Image processing of the HREM data involved background noise reduction and phase extension using a combination of software programs (Digital Micrograph, CRISP, HREM filters, and VEC).

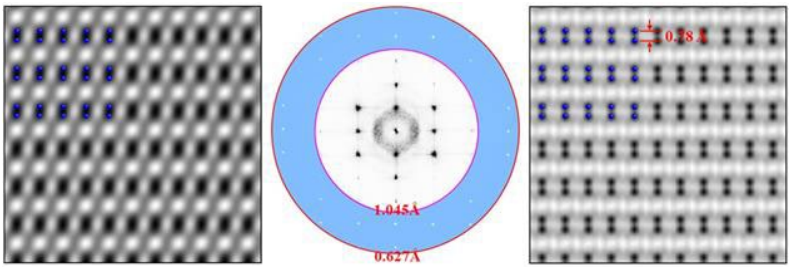
Results
A high-resolution (HR) image of the Si [211] projection with an atomic resolution of 1.2 Å was obtained using a high-voltage electron microscope (HVEM). Additionally, a precession electron diffraction (PED) pattern satisfying the quasi-kinematical condition was acquired with an enhanced spatial resolution of 0.63 Å using a beam precession system. By applying the phase extension technique to these combined data, Si atomic columns with

an atomic spacing of 0.78 Å in the Si [211] projection were successfully resolved.

Conclusion

The HVEM and PED combination method has demonstrated its potential to achieve high resolution even in thick samples by leveraging HVEM's high penetration power and PED's ability to minimize dynamical effects. By employing this technique, the reduction in resolution caused by sample thickness in high-resolution imaging analysis using Cs-corrector can be partially compensated, which is expected to significantly aid in the accurate analysis and understanding of the structure and properties of nano-crystals.

Graphic:



Keywords:

HVEM, PED, Phase extension technigue

Reference:

S. H. Oh, Y. J. Kim, H. S. Kim, Experiment of usefulness of IWFR analysis for HVTEM images with a series of defocus steps obtained from a relatively thick crystal, Korean J. Microscopy, 38(4) 363-374 (2008)