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主 論 文 の 要 旨

論文題目 Studies of Image Processing for Phase Restoration in Electron Holography （電子線ホログラフィーにおける再生位相の修復に関する画像処理的研究）

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論 文 内 容 の 要 旨

At present, new products and even new industries rely on radical advances in materials. However, it is also important to make incremental improvements using currently available materials.

In-situ observations of phenomena are important in material science, where materials are observed and recorded in situations where they are used or produced in practice. In many cases, chemical intermediates are synthesized in-situ during various processes.

In-situ off-axis electron holography allows us to study accurate phase changes of electron waves in a material in various active conditions with different experimental parameters. In particular, off-axis electron holography, which uses an image hologram, has the advantage of separating a reconstructed phase image from its complex conjugate image.

The phase shift information can be directly related to the inner electrostatic potential and the in-plane component of the magnetic induction in the specimen, and electron holography has enabled the investigation of nanoscale electromagnetic fields, which play an important role in many nanostructured materials and devices, including p-n junctions in semiconductors, nonvolatile magnetic storage media, and some spintronic devices.

However, the reconstructed phase images often contain imperfections after they are reconstructed from holograms.

With the development of computational techniques, the digital image processing can be used to improve the images obtained by electron microscopy. The present study aimed to apply digital image processing to eliminate the imperfections that occur during the reconstruction of electron holograms. A novel method of image processing for phase imperfections in electron holography has been established and applied to the actual holograms.

Firstly, the background and aims of the study are introduced, including in-situ off-axis electron holography, phase reconstruction, some digital image processing methods for in-situ off-axis electron holography and including aberration correction for high resolution electron

microscopy. The study of the procedure of hologram generation, recording and reconstruction determines which processing methods should be picked up. Many processing methods are described as the efficacious methods on the hologram processing for smoothing and noise removing.

Secondly, the phase imperfections are studies and the phase jumps in the reconstructed phase are classified firstly as two main types according to their cause. One type of phase jump is the well-known 2 π phase jump during the digital reconstruction process, which occurs because the reconstructed phase falls within a range of $[-\pi, \pi]$, and can be unwrapped and connected in a smooth manner using the appropriate software. The other type of phase jump usually occurs in the areas with low contrast of the electron wave amplitude. This type of phase jump has not been studied and solved effectively so far. It is found by analysis of the interference fringe that the wrong connection of interference fringes in those specific areas is the cause of the other type of phase jump. A new method of digital image processing is proposed and applied to the restoration of the phase imperfections in reconstructed phase images due to the low contrast of the electron amplitude. The proposed technique enables to obtain comparatively accurate phase information for studying the inner electrostatic potential without changing the conditions in actual applications.

Thirdly, this new digital image processing method is applied to a crystal structure image simultaneously with an aberration correction procedure. The singularity- restored phase image shows a good coincidence with the crystal structures reported. The method can be very useful and effective under severe conditions, such as in-situ holographic experiments.

Fourthly, the undulation noise which is an artifact in the processing is studied, as it sometimes occurs in the reconstructed phase images. A comparison of the two phase image before and after processing shows that the unevenness in the thickness of the interference fringes in the binary image is the source of such undulation noise. The elimination of this undulation noise is accomplished after making the interference fringe thickness even.

Finally, the simulation of holograms with noise including Poisson noise and Gaussian noise in a low electron luminance is addressed. Poisson noise and Gaussian noise are two main types of noises that may occur when capturing holograms. The interference fringes may not be distinguished for the low electron luminance, because a small number of electrons hardly form the clear fringes. The proposed processing methods are executed for noise elimination and singularities restoring using the simulation of hologram. The implementation demonstrates that the proposed processing method is effective and it has practical value for processing electron holograms in the noisy and low electron luminance situations.

In conclusion, a new method of digital image processing for phase imperfections in electron holography has been proposed to remove the influence of imperfections on the reconstructed phase. The quality of the reconstructed phase image was improved by removing imperfections in the phase. The phase image clearly showed the structure of the crystal specimen coincidence with the model structure. The developed method contributes to the correction of inaccurate phase information and this technique enables the study of the inner electro-

static potential and the in-plane component of the magnetic induction at nanometer and subnanometer scales.