

## Differential Phase Contrast Imaging with Reduced Dynamical Diffraction Effect

Akiho Nakamura<sup>1</sup>, Yuji Kohno<sup>1</sup>, Hirokazu Sasaki<sup>2</sup>, and Naoya Shibata<sup>3</sup>

<sup>1</sup> JEOL Ltd., 3-1-2 Musashino, Akishima, Tokyo 196-8558, JAPAN.

<sup>2</sup> Furukawa Electric Ltd., 2-4-3 Okano, Nishi-ku, Yokohama 220-0073, JAPAN

<sup>3</sup> The University of Tokyo, 2-11-16, Yayoi, Bunkyo-ku, Tokyo 113-8656, JAPAN.

Phase contrast imaging in STEM has become a very exciting field after the rapid developments in segmented/pixel type detectors, and some powerful imaging techniques have been studied including Differential Phase Contrast (DPC) [1,2] and ptychography [3]. Particularly, DPC is a promising method for characterizing local internal electric and/or magnetic fields of functional materials (ex. magnet, semiconductor device)

However, one of the most critical problems on the DPC imaging is artifact from diffraction contrast (ex. bend contours or equal thickness fringe): the acquired images of internal electric and/or magnetic field are severely disturbed by the waving background contrasts due to diffraction contrast. This is particularly critical when we perform DPC STEM for a sample along low index crystal axis at low magnification (that is, large field of view), where many diffracted beams are strongly excited and an intensity distribution of CBED patterns becomes highly complex, due to intensity exchanges between diffracted and direct beams, resulting in confusing image contrasts.

To overcome such problems, we adopted the idea of Precession Electron Diffraction (PED) [4] into DPC STEM imaging to avoid these diffraction contrasts. The PED is known as a method for suppressing dynamical scattering effects in electron diffraction. Thus, we tried to apply the PED technique to DPC imaging (“precession DPC”) to reduce diffraction contrast.

A *p-n* junction in GaAs semiconductor was selected as a model sample. The sample was prepared by FIB, where the thickness of the sample was controlled to be about 200 nm. Detail information about this sample can be found elsewhere [5]. The same sample was characterized by DPC STEM in the previous study [6], where the inner electric field was clearly observed and analysed in a quantitative manner.

The STEM observation results reported in this paper was performed using an aberration corrected microscope (JEOL, JEM-ARM200F) equipped with an 8-segmented STEM detector (JEOL, SAAF Octa). The optical condition for DPC STEM was set to be high sensitivity mode (STEM low-mag, incident angle  $\sim 150$   $\mu$ rad, effective camera length  $\sim 4000$  cm). The DPC signals were calculated from the second layer of SAAF Octa detector (signals from channel 5~8).

In the experiment, the GaAs [110] zone axis was aligned along the optic axis, and DPC images were acquired with and without precession control. In the former case, the optical system was fixed, and the relative angles between the incident beam and the specimen were manually controlled by X/Y tilt of the specimen holder. The range of precession angle was  $\pm 0.5$  degree for X and Y directions around the [110] axis, where the tilting step was set to be about 0.1 degree. A set of raw images was acquired for each step, so that we got  $11 \times 11 = 121$  data sets from the same sample region. These sequential images were aligned by cross correlation processes, stacked and averaged into single data set, and then used for calculating the “precession DPC” image. For reference, a DPC image without special care for diffraction contrast was also taken along the [110] crystal axis direction.

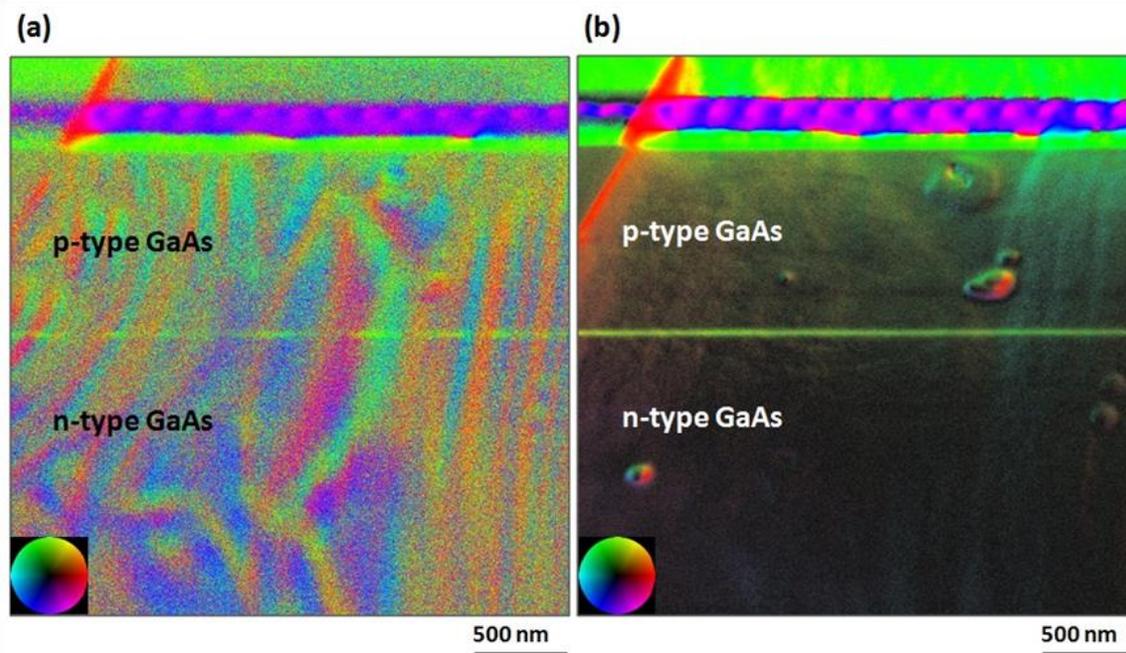
Figures 1-(a) and 1-(b) show the DPC images of the  $p$ - $n$  junction in GaAs. The calculated strength and direction of field are represented by brightness and colour, respectively (see the legends on each figure). Because internal electric field should be formed from n-type to p-type region, the DPC contrast at  $p$ - $n$  junction is in yellow-green in our observation.

Figure 1-(a) is the standard DPC image without precession control. The contrast of  $p$ - $n$  junction is severely disturbed by the strong background diffraction contrast. The  $p$ - $n$  junction seems to be fragmented by waving background contrast. Because of such strong diffraction contrast, it is difficult to correctly analyse local electric field distribution. Figure 1-(b) shows the DPC image with precession control. The diffraction contrast of this image is reduced to be negligibly small, and the  $p$ - $n$  junction can be now clearly visualized.

It should be mentioned that, in the previous studies, such clear DPC contrast can be achieved with very large specimen tilt (upto 10 degree in typical) to avoid strong diffraction contrast. However, our result demonstrates that it is possible to suppress the diffraction contrast even along the low index crystal axis by the “precession DPC” method, without altering the original field information [7].

References:

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**Figure 1.** DPC STEM results for  $p$ - $n$  junction in GaAs viewed along [110] axis, (a) *without* precession control and (b) *with* precession control. The  $p$ - $n$  junction is appeared as straight horizontal lines in yellow-green at the middle of each figure. The strength and direction of calculated field are represented as brightness and color, respectively. Some small color rings on bulk GaAs regions are contamination makers, prepared for positional alignments done by cross correlation calculation.