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Monolithic Multi-Grating Diffraction in a Convergent Electron Beam

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Electron interferometers have been utilized in electron exit-wave reconstruction [1], imaging magnetotactic bacteria [2] and many other applications [3, 4]. Although most electron interferometers use a biprism as a beam splitter, interferometers based on crystalline [5] and nanofabricated gratings [6] have also been constructed. Gratings offer the possibility of interferometry in a standard SEM/TEM but require very precise alignment of position and orientation [5, 6]. To address this challenge, we designed an interferometer for a TEM based on a monolithic three-crystal grating (we refer to this as a multi-grating) as shown in figure 1(a), fabricated by focused ion-beam milling.

We used both parallel- and convergent-beam electron diffraction through the multi-grating (MG-PBED and MG-CBED) to characterize the fabricated gratings. Figure 1(b) shows a ray diagram illustrating the formation of a diffraction pattern (DP) in the back focal plane (BFP) of the objective lens in a TEM with a parallel beam. In MG-PBED, we see that first-order diffraction spots arising from the 1st and 2nd crystal layers overlap in the BFP when the three gratings are well aligned. Figure 1(b) also shows the experimentally observed DP from MG-PBED. The observed DP is identical to that produced by a single layer of Si (110), proving that the three gratings are translationally and rotationally aligned.

MG-CBED yields a DP with an array of satellite spots, as shown in figure 1(c), which cannot be explained by double diffraction from a single crystal. Unlike conventional convergent beam electron diffraction (CBED), which looks at disks at or close to the BFP, we focused the DP by controlling the intermediate lens (IL) and thus moving to the 2nd crossover plane (CP) as shown in figure 1(c) (this figure only shows first-order diffraction from two gratings for simplicity). Here the diffracted beams from the 1st and 2nd gratings are focused at horizontally displaced spots. By taking all diffraction orders from the gratings into account, we can build up the DP from figure 1(c).

In order to verify a mechanism of this unconventional diffraction we measured the spacing d between the <000> and <111> diffraction spots from a single layer of silicon as a function of vertical displacement z in the TEM column under identical beam conditions; the results are plotted in figure 2. The change in d as a function of z confirms that the beam is convergent and allows us to measure the convergence angle α. Further, we placed the two-grating region of the multi-grating in the two-beam condition and recorded the DP for α = 10 mrad and α = 1 mrad. A satellite spot can be seen in figure 3(a) near the <220> diffraction spot. As α is reduced the satellite spot almost merges with the <220> spot in figure 3(b), as expected from our proposed mechanism.

This diffraction mode can be used for applications in TEM metrology such as characterizing beam convergence angle (as shown here) and grating periodicity, and in splitting CBED [7].

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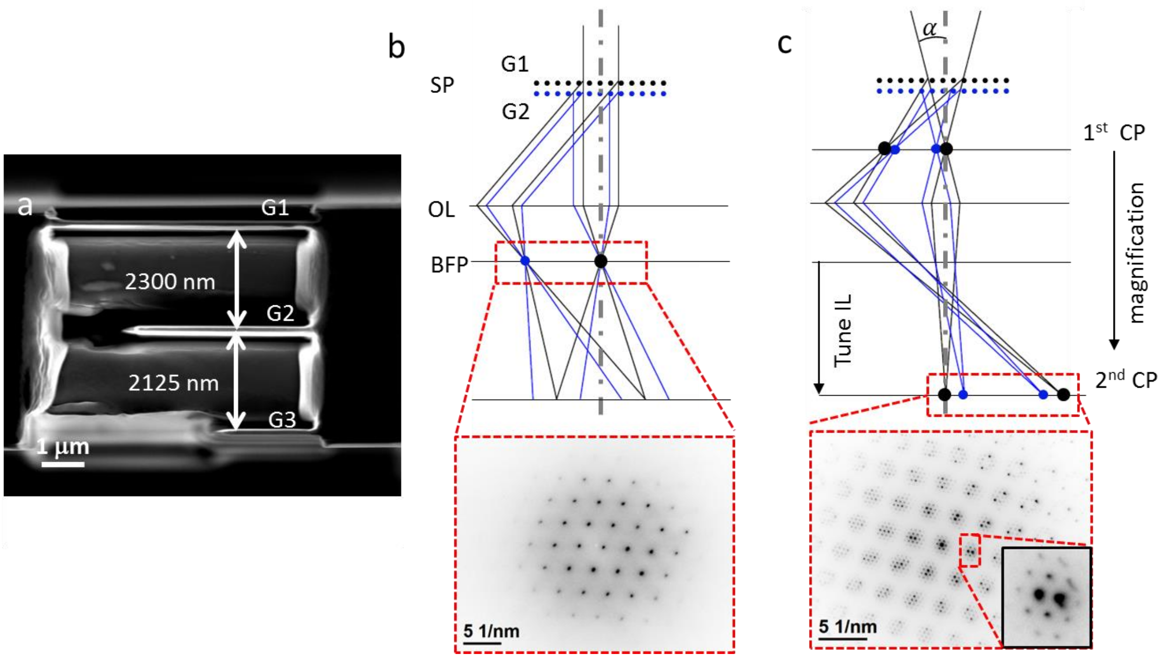

Figure 1. (a) Monolithic three-crystal grating fabricated from Si by FIB. The Si has a zone-axis of (110). (b) Ray diagrams and experimentally observed DPs for MG-PBED and (c) MG-CBED. Black and blue rays represent diffraction from G1 and G2, respectively. (G1: first grating, G2: second grating, SP: sample plane, OL: objective lens, BFP: back focal plane, CP: crossover plane, α: convergent angle)

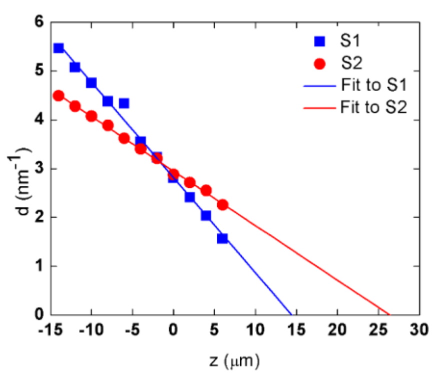

Figure 2. Proof-of-theory experiment for MG-CBED based on the ray diagram Figure 1c. The spacing d between <000> and <111> in reciprocal space was measured by changing the z-height of sample (grating) position for two different convergence angles of 10 mrad (S1) and 5 mrad (S2).

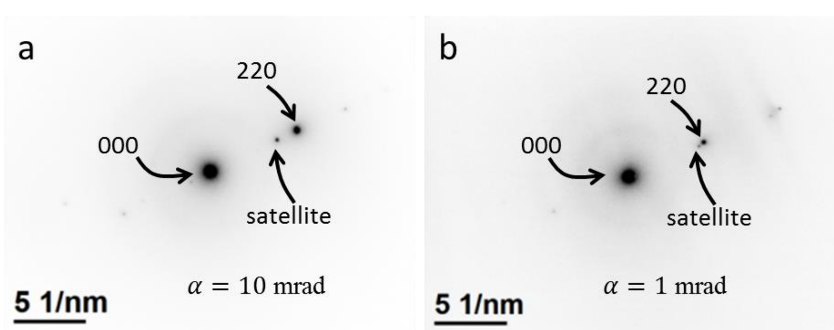

Figure 3. MG-CBED with two-beam condition for two different convergent angles. (a) $\alpha = 10$ mrad and (b) $\alpha = 1$ mrad.

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