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IT-2-O-1555 Imaging of light elements by annular dark-field Cs-corrected STEM

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Nowadays, many crystalline lattices can be imaged directly at atomic resolution in Cs-corrected STEM. Recently, it was shown that light and heavy elements in crystalline lattices can be detected with an ABF method[1] or with a double-detector STEM method.[2] However, imaging of atomic columns of light elements by ADF method remains challenging. Particularly, the observation of light element columns at the interface between two different materials is still a difficult issue. In this work, we were able to detect directly and simultaneously the N and C atomic columns at the GaN-SiC interface and within the GaN and SiC materials. Additionally, the O atomic columns in a $SrTiO_3$ single crystal were also observed by our method. We have studied the influence of imaging conditions on the appearance of N and C atomic columns in the GaN and SiC materials. The obtained results are discussed and are supported by image simulations.

The GaN thin film for this study was grown on 6H-SiC(0001) substrate by ion-beam assisted molecular beam epitaxy. STEM experiments were performed on a probe Cs-corrected Titan[3] G2 60-300 microscope operated at 300 kV. A probe forming aperture of 20 mrad was used. Cross-sectional samples for STEM work were prepared by FIB technique. To improve the surface quality of the TEM specimens and to reduce the samples thicknesses, a focused low-energy argon ion milling (NanoMill system) was applied.[3] Ion energies from 900 eV down to 200 eV were applied to remove implanted Ga ions and amorphous regions caused by the FIB. Image simulations were performed with the xHREM/STEM software package.

Figures 1 and 2 show the results of our work.[4] We found that by adjusting the settings of HAADF detector and defocus value in STEM, the light element columns at the GaN-SiC interface and within the w-GaN, 6H-SiC and $SrTiO_3$ lattices can be imaged using only a single HAADF detector. We concluded that image simulations for interpretation of atomic-resolution STEM images are only necessary when the probe forming aperture angle overlaps the inner angle of an annular STEM detector or when a complex defect structure is observed in a studied TEM sample. Our method works well using either ADF or HAADF detector, because their angular ranges and defocus values can be easily adjusted on any Cs-corrected STEM. Thus, on TEM systems equipped with only one HAADF detector, the technique can be used without any doubt and upgrades to an ABF detector.

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2. Y. Kotaka, *Appl. Phys. Lett.* **101**, 133107 (2012).
3. D. Poppitz, A. Lotnyk, J.W. Gerlach, B. Rauschenbach *Acta Mater.* **65**, 98 (2014).
4. A. Lotnyk, D. Poppitz, J.W. Gerlach, B. Rauschenbach *Appl. Phys. Lett.* **104**, 071908 (2014).

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Cs-corrected: aberration-corrected; STEM: scanning transmission electron microscopy; ABF: annular bright-field; ADF: annular dark-filed; HAADF: high-angle ADF; FIB: focused ion beam; w-GaN: wurtzite-type GaN; i: detector inner angle; o: detector outer angle.

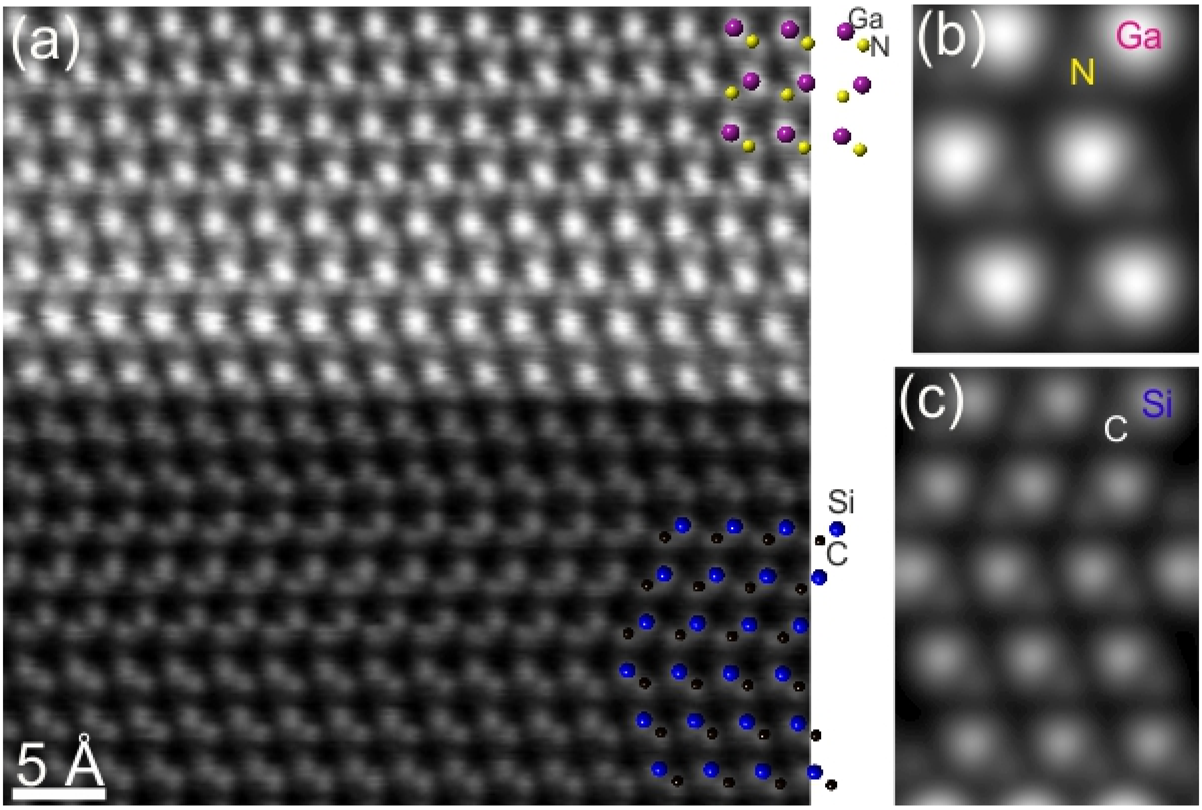

Fig. 1: (a) Atomic-resolution STEM image of the GaN-SiC interface taken with a HAADF detector (i20.4-o124.6 mrad) and schematic representation of w-GaN and 6H-SiC lattices along the [2-1-10] zone axis. (b) and (c) Simulated images of w-GaN and 6H-SiC, respectively, at 5 nm underfocus. The TEM sample thickness is measured to be about 16 nm.

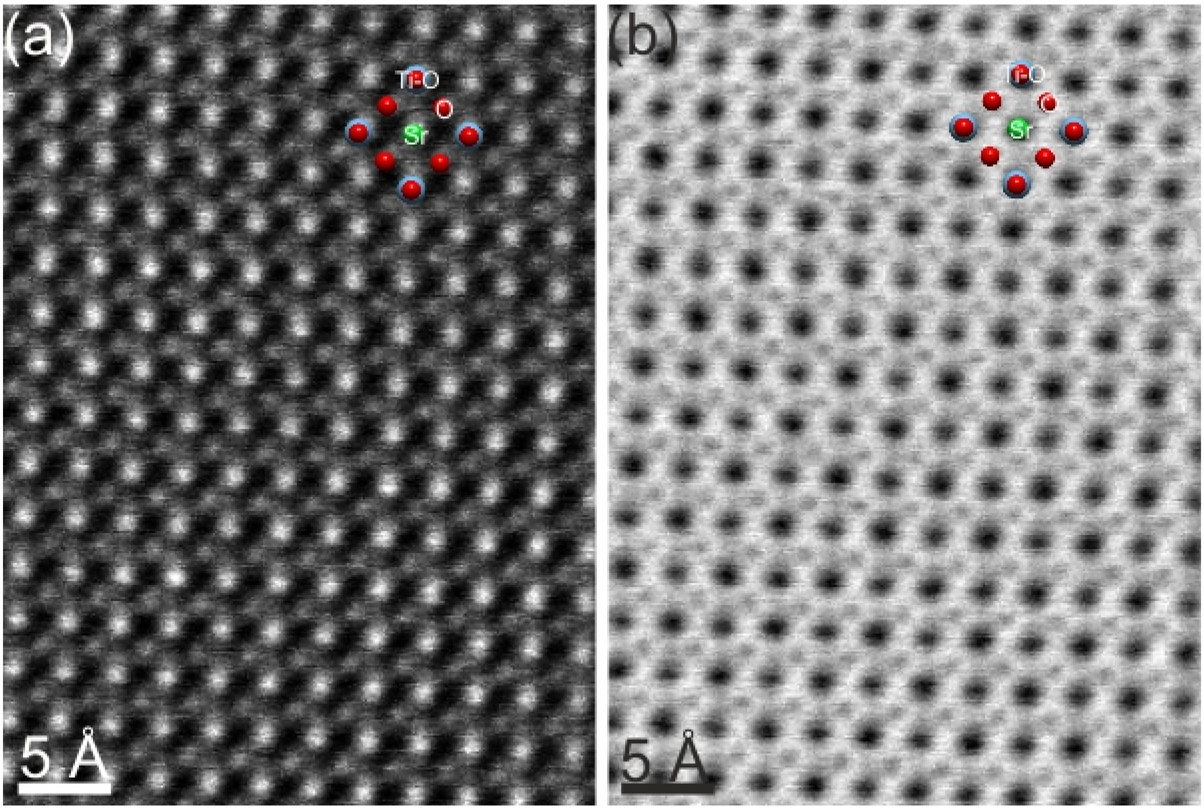

Fig. 2: High-resolution STEM images of $SrTiO_3$ acquired with (a) ADF (i19.1-o106.5 mrad) and (b) ABF (i10.1-o19.1 mrad) detectors. The insets in (a) and (b) show the $SrTiO_3$ structure viewed along the [001] zone axis. The TEM sample thickness is measured to be about 60 nm.