Composition analysis of InGaN quantum wells by STEM-HAADF

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The knowledge of the alloy composition of thin films is of particular interest for the understanding of important optical and electrical properties of devices like light emitting diodes (LED) based on InGaN quantum wells (QW) or AlGaN/GaN high electron mobility transistors (HEMT). One possible method of an alloy composition analysis is high angle annular dark field imaging in scanning transmission electron microscopy (STEM-HAADF). The main advantage of STEM-HAADF is that the image intensity mainly correlates with the mean atomic number Z of the probed volume [1,2] and chemical information can be obtained by comparing image intensities [3]. This is why this technique is also known as Z-contrast. Furthermore, STEM-HAADF provides almost unambiguous information about the positions of atomic columns over a wide range of lens defocus and specimen thickness since the image formation is based on incoherent scattering [4]. A quantitative composition analysis of thin AlGaN layers and InGaN QWs by STEM-HAADF was recently demonstrated by Rosenauer et al [5,6]. However, for a precise quantitative determination of the alloy composition, several effects like strain relaxation at the specimen surface [7] and static atomic displacements (SAD) [8] usually have to be taken into account. As a result, a simple relationship as the commonly used $Z^{1.7}$ dependency of the contrast is often not valid and time consuming simulations of the HAADF contrast are necessary. In our work we systematically study the influence of experimental parameters such as like camera length, crystallographic projection and specimen thickness on the HAADF image, using the example of InGaN QWs with nominally 17% In. The major goal is to find imaging conditions for which the HAADF contrast mainly corresponds to the chemical composition and disturbing influences have only a minor effect. This would allow a quantitative composition analysis without extensive image simulations. The studies were carried out with a conventional FEI Titan operating at 300 kV and with a semi-convergence angle of 9.0 mrad for the electron probe. In our experiments we found an essentially different behavior of the HAADF contrast for the [11-20] and [1-100] projections. (i) While in the [11-20] projection the InGaN/GaN contrast strongly depends on the specimen thickness, it is almost independent on thickness (in the range between 0 to 150 nm) for the [1-100] projection. (ii) Additionally we observed that the contrast of the InGaN QWs relative to the surrounding GaN increases for decreasing inner acceptance angle of the ADF detector (= increasing camera length) for both crystallographic directions. However, this effect was more pronounced in the [11-20] projection. (iii) A direct comparison for identical camera length and approximately same specimen thickness (Fig. 1) reveals the surprising results that the InGaN/GaN contrast is much higher for the [11-20] projection (by a factor of 2). In order to understand the origin of these observations, we performed multislice and Bloch-Wave simulations. The experimental findings are well reproduced in the simulations and we gained two important insights. First, we found that SADs in the InGaN alloy disturb electron channeling and lead to an extra diffuse scattering, especially into the low-angle region. Thus, increasing the camera length (= including the low-angle region to the ADF detector) enhances the contributions of SADs to the image and increases the InGaN/GaN contrast. Second, the simulations showed that electron channeling is less pronounced along the [1-100] direction. Therefore the influence of SADs on the image contrast is reduced in this projection. That is precisely the reason for the lower InGaN/GaN HAADF contrast as well as the weaker thickness dependency of the HAADF contrast in the [1-100] projection. In summary we conclude that the [1-100] projection is much more suitable for a quantitative composition analysis in III-nitride semiconductors than the [11-20] orientation because of the lower influence of experimental parameters on the HAADF contrast.

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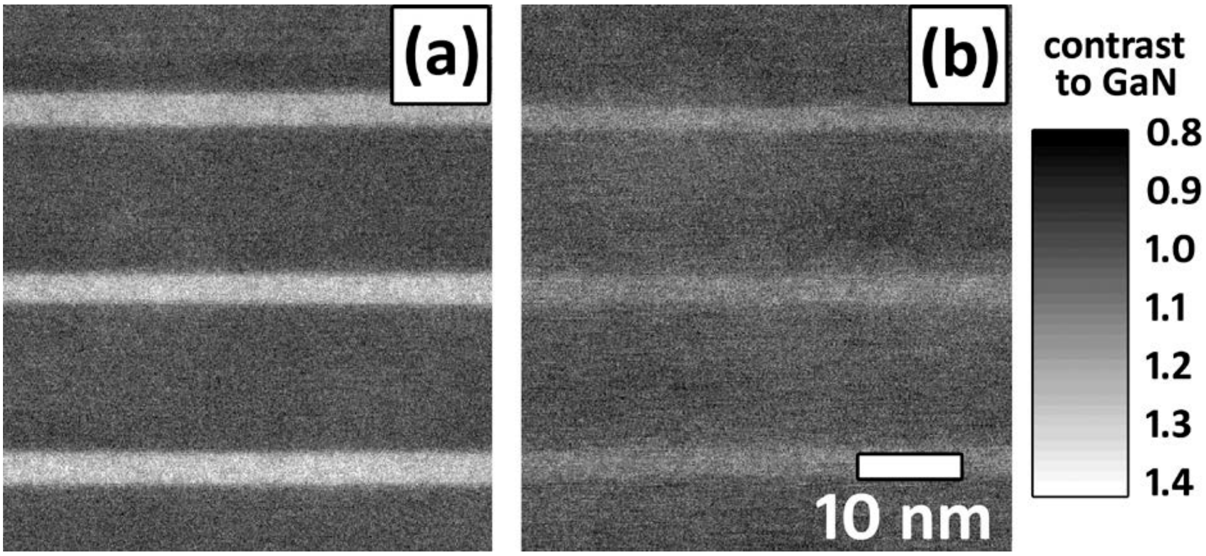

Figure 1. *STEM-HAADF images of InGaN QWs with nominally 17% In surrounded by GaN barriers. Image (a) was recorded in the [11-20] projection, image (b) in the [1-100] projection. In order to compare the InGaN/GaN contrast both images were normalized to the GaN background intensity and are displayed on the same contrast scale. The camera length is 196 mm (=55 mrad inner detector angle) and specimen thickness approximately 130 nm for both images.*