Structural characteristics of dilute nitride III/V semiconductors

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Keywords: dilute nitride semiconductors, structure factor, atomic displacement

III/V semiconductor materials containing dilute amounts of Nitrogen exhibit extreme application potential due to their specific optoelectronic properties. Among the potential applications are lattice matched (GaIn)(NAs) solar cells on Ge substrates, 1.3 and 1.55 µm lasers for telecommunication applications as well as the integration of a direct bandgap Ga(NAsP) material on silicon substrates. The latter will path the way towards optically integrated circuits on the electronic material Si.

This class of material systems is however metastable mainly due to the large difference in covalent radius between the Nitrogen and the other atoms occupying the group V lattice sites. The alloys can be grown in different composition regimes under extreme non-equilibrium growth conditions by metal organic vapour phase epitaxy or molecular beam epitaxy. However, due to the metastability of dilute nitride materials, structure formation processes occur, which would not be expected for stable materials. Hence, local clustering, phase separation or ordering phenomena are important and need to be researched on a nano-scale.

To derive the composition on short length scales, we use a combination of several transmission electron microscopic (TEM) techniques. Dark field imaging with so-called chemical sensitive reflections in tandem with structure factor calculations yields information on local strains as well as compositions on a several-nanometer length scale. One can show, that the static displacement of the group-III-atoms, which is introduced by the N [1] needs to be taken into account and that the structure factor needs to be recalculated.

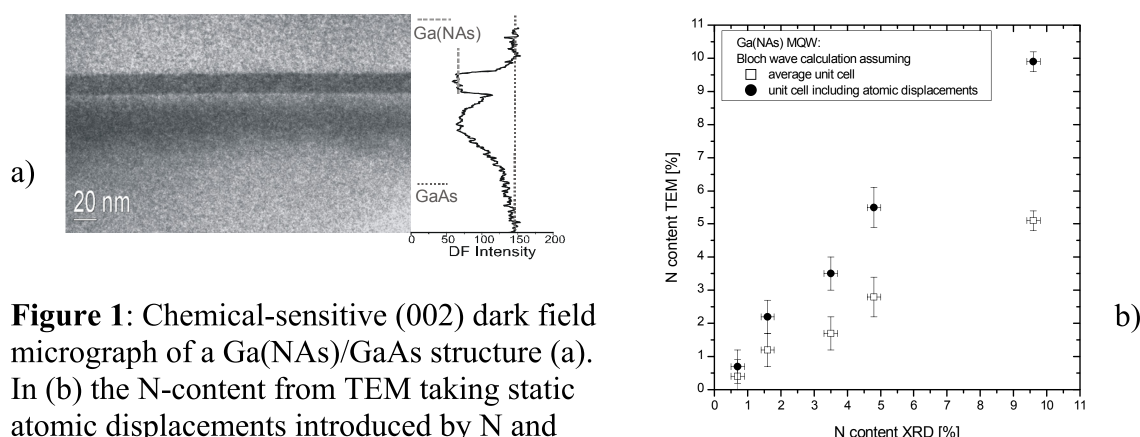

Figure 1: Chemical-sensitive (002) dark field micrograph of a Ga(NAs)/GaAs structure (a). In (b) the N-content from TEM taking static atomic displacements introduced by N and neglecting them is compared to the N content derived from X-ray diffraction.

Figure 1 shows [2] a chemical sensitive (002) dark field (a) of a Ga(NAs)/GaAs quantum well. The N content derived from this kind of images for different compositions is compared in (b) to the N-content in the same samples, but derived from X-ray diffraction.

DOI: 10.3217/978-3-85125-062-6-383 , © Verlag der TU Graz 2009

Both methods only yield comparable compositions, if the static atomic displacements introduced by the N are taken into account in the structure factor calculation. These calculations can also be used to quantify the displacements of atoms on a sub-nm scale, which is important for device characteristics. This significant displacement can also be detected in Z-contrast high angle annular dark field images of Ga(NAs)/GaAs structures, where the N-containing region exhibits bright contrast compared to the GaAs matrix under all imaging conditions.

The quaternary (GaIn)(NAs) material is more stable than the ternary Ga(NAs) in thermal annealing cycles, what can be shown using composition evaluation by lattice fringe analysis [3]. In these measurements it is shown that under comparable annealing conditions the N distribution in Ga(NAs) becomes inhomogeneous, hence the material phase separates, whereas the N distribution throughout the (GaIn)(NAs) layer stays unchanged (Fig.2).

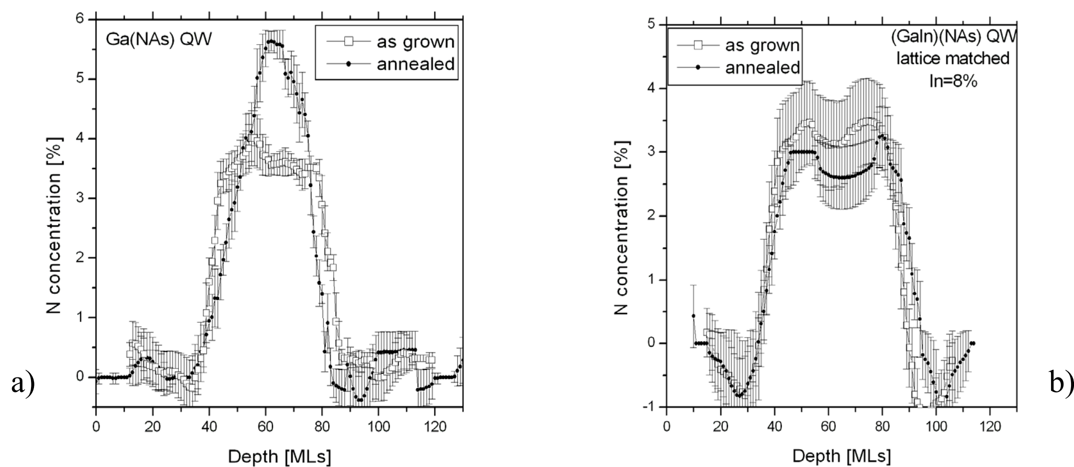

Figure 2: Nitrogen distribution accross Ga(NAs)/GaAs (a) and (GaIn)(NAs)/GaAs (b) quantum wells before and after identical thermal annealing procedures [3].

This behaviour can be understood from the evaluation of chemical and strain energy in the different compounds upon growth and after thermal annealing.

This paper will summarize our present knowledge on the nanostructure of dilute nitride III/V semiconductors - also in dependence on the composition as well as in dependence on the thermal history of the samples - as derived from transmission electron microscopic investigations. It will be shown, how different TEM techniques in combination with theoretical modelling of stable crystal structures as well as of electron diffraction can significantly help in understanding intrinsic properties and structure formation processes in these extremely interesting alloys. We will also demonstrate for selected examples, how an understanding of the structural properties can path the way towards improved devices.

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W. Grogger, F. Hofer, P. Pölt (Eds.): MC2009, Vol. 3: Materials Science,
DOI: 10.3217/978-3-85125-062-6-383 , © Verlag der TU Graz 2009