Correlative investigation of Mg dopant in GaN p-n junction by atom probe tomography and off-axis electron holography

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Atom probe tomography (APT) is a powerful technique allowing the direct measurement of the chemical composition and 3D distribution of the atoms in a sample [1]. APT is widely used for the investigation of dopants in semiconductors such as gallium nitride (GaN) alloys which are widely used in optoelectronics [2]. In these materials, the dopant distribution is crucial to control the electrical properties for high performance devices [3]. In this work, we used APT to investigate the chemical composition of Mg in the matrix and precipitates, to estimate the amount of dopant, which is potentially active in a GaN p-n junction.

Several studies have reported the strong dependence of analysis parameters on the GaN chemical composition [4]. In order to obtain reliable and quantitative Mg composition measurements, we first studied the variation of the composition of Ga, N and Mg as a function of the surface electric field. Figure 1 shows the APT measurements for different estimated fields for a dedicated GaN layer doped with Mg (1.3E20 cm^{-3}) where the expected concentration is only obtained at low electric field conditions. Using this information, a GaN p-n junction doped with Mg (1E20 cm^{-3}) and Si (5E19 cm^{-3}) grown by metalorganic chemical vapor deposition has been investigated by APT. Figure 2(a) shows the 3D distribution of Mg atoms (in blue) where Mg-rich clusters appear in the p-doped region. The total Mg concentration in the p-type layer is estimated at 1.6E20 ±0.3E20 cm^{-3} which is in good agreement with SIMS measurements. Cluster identification algorithms have been used to determine that they contain a low number of Mg atoms (an average of 48 atoms). The concentration of Mg in the matrix (outside clusters), which is assumed to be potentially electrically active, is estimated at 1.3E20 ±0.3E20 cm^{-3}. These measured compositions demonstrate that even if Mg clustering is occurring in p-doped layer, most of Mg atoms are dispersed in the matrix. Therefore, these clusters will not affect considerably the potentially active concentration. Concerning the n-region, the distribution of Si dopants cannot be determined by APT due to its overlap with N peaks in the mass spectrum. Nevertheless, Mg chemical profile across the junction (Figure 2(b)) shows no abrupt interface and a clear diffusion of Mg in the n-regions.

Both Mg clustering (in p-region) and the diffusion of Mg atoms into the Si doped layers (in n-region) causes compensation effects which degrades the electrical properties. To better understand the influence of the Mg distribution observed by APT on the electrical properties, these results are correlated with off-axis electron holography in a transmission electron microscope which directly measures the dopant electrical activity in p and n regions [5]. Figure 2(c) shows a potential map where the p region has a dark contrast arising from the active dopants. The corresponding potential profile (Figure 2(d)) shows a depletion width of 20 ±5 nm at the junction. In conclusion, despite the Mg-rich clusters and the Mg diffusion observed by APT, a sharp electrical junction is formed.

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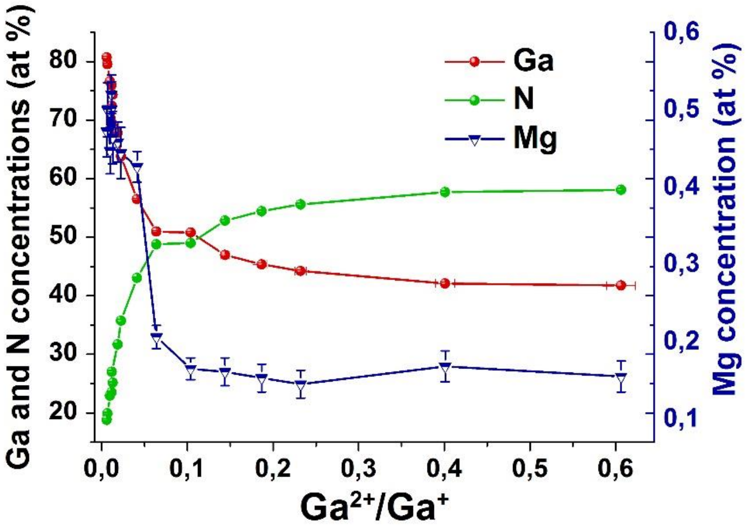

Figure 1: Comparison of Ga (in green), N (in red) and Mg (in blue along the secondary axis) compositions obtained by APT, as a function of the charge state ratio representing the strength of the field on the specimen.

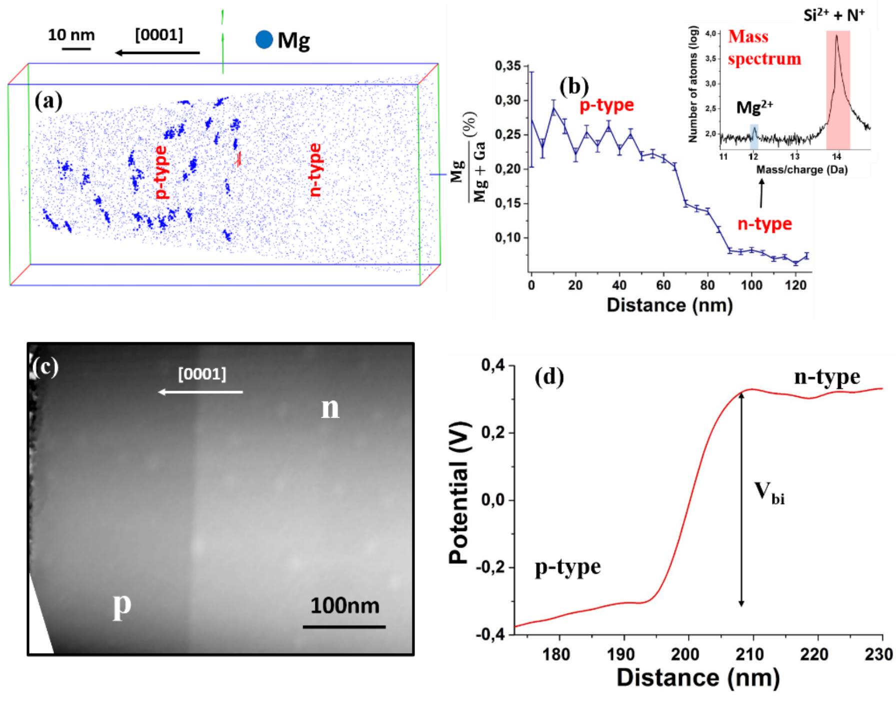

Figure 2: a) 3D distribution of Mg atoms in blue where Mg-rich clusters are shown. b) Mg concentration profile across the p-n junction. Inset: mass spectrum in the n-region where Mg^2 peak appears. c) Potential map of the p-n junction acquired at room temperature. d) Electrostatic potential profile drawn across the p-n junction.