Insight in Mg dopant incorporation in GaN by atom probe tomography and off-axis electron holography

Amichi, L.[1,2], Mouton, I.[1,3], Cooper, D.[1,3], Boureau, V.[1,3], Dussaigne, A.[1,3], Vennéguès, P.[4], De Mierry, P.[4], Grenier, A.[1,3], Jouneau, P.[1,2] and Bougerol, C.[1,5]

[1] Université Grenoble Alpes, France, [2] CEA - INAC, France, [3] CEA - LETI, France, [4] CRHEA - NICE, France, [5] Institut Néel, France

The control of p-type doping is necessary for improved semiconductor devices based on GaN materials. Mg is the most promising p-type dopant though it has a relatively high ionization energy. A concentration in the range 10^{19} to 10^{20} cm^{-3} is needed for hole concentrations above 10^{18} cm^{-3} at room temperature. For metalorganic chemical vapor deposition growth, Mg concentrations above ~$2x10^{19}$ cm^{-3} results in the formation of defects such as Mg-V_N complexes, acting as compensation centers [1], and Mg-rich pyramidal inversion domains (PIDs)[2] . Both of these effects explain the observed drop in carrier concentration. Furthermore, the growth temperature (T_{growth}) has a significant impact on the Mg-dopant incorporation in GaN [3]. Using APT, we are able to determine the atomic distribution of the Mg and measure directly the potentially active dopant by removing identified PIDs appearing as Mg clusters. The active Mg generates carriers which create electrostatic potentials inside the sample. They are directly measured by off-axis electron holography in a transmission electron microscope. For this purpose, we have correlated both techniques to investigate both the Mg and electrical properties as function of Mg concentration and T_{growth}.

We first analyzed a GaN stack with different Mg concentrations grown at 950 °C. APT reconstruction (Figure 1(a)) shows Mg rich clusters for both layers which are probably related to PIDs. A higher cluster density in the layer doped at 1E20 cm^{-3} is observed compared to the layer doped at 5E19 cm^{-3}. Here, the concentration of potentially active Mg is higher in the most doped layer (around 1.5 times). Electron holography has been performed on the specimen at 400 °C to increase the measurable dopant activity [4]. The acquired potential map is shown in Figure 1(b) where the doped regions appear darker. The potential profile highlights an increase in the potential at the interface between layers due to a decrease in the hole concentrations. In conclusion, for a high Mg concentration we observe the highest density of clusters, however, despite this, in this region we have the generation of the highest holes density.

Another GaN doped multilayer grown at higher temperatures (between 990°C and 1090°C) separated by non-intentionally doped (NID) layers was analyzed. APT reconstruction shows the presence of Mg clusters in doped layers whose size increases with the T_{growth} (Figure 2(a)). At the same time, the total Mg concentration (green curve in Figure 2(b)) decreases as well as the Mg concentration outside the clusters (black curve in Figure 2(b)). In addition, we have observed a homogenous diffusion of Mg in the NID layer increasing at the highest T_{growth}. Electron holography has been performed again at 400 °C and the potential map is shown in Figure 2(c). A strong variation is observed between doped and undoped layers below the surface and decreases with T_{growth}. Figure 2(d) shows the corresponding potential profile where a significant decrease in the built-in potential is observed with the increase of T_{growth}. We show here that there is a reduction of carriers in the layers grown at high temperature.

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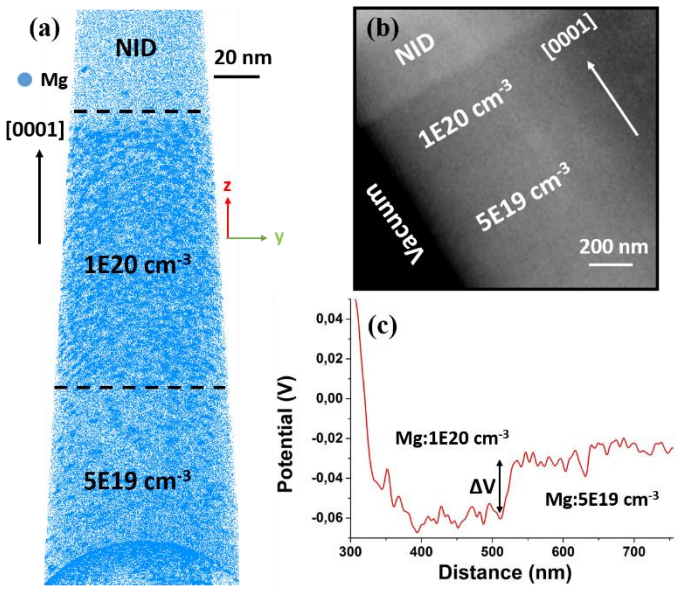

Figure 1: (a) 2D projection of Mg atoms detected by APT in blue (b) Potential map of the sample acquired at an in-situ heating temperature of 400 °C. (c) Potential profile across the two GaN doped layers at 1E20 cm^{-3} and 5E19 cm^{-3}.

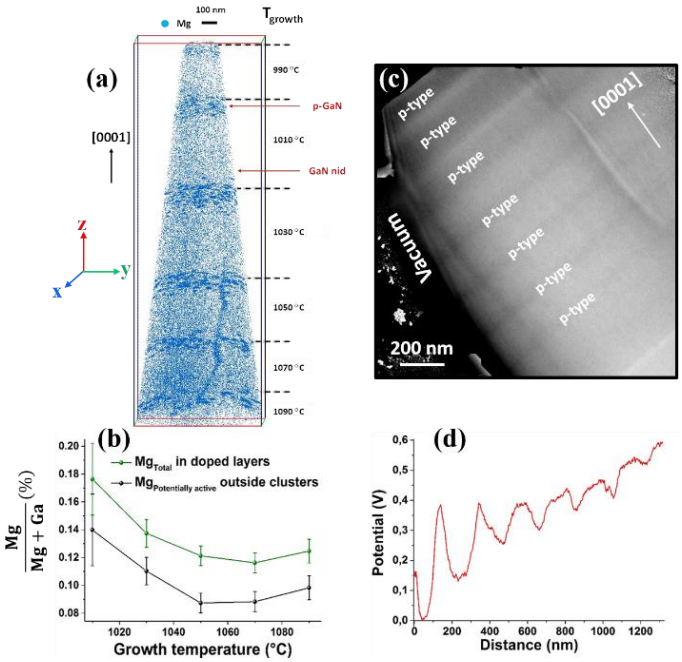

Figure 2: (a) APT 3D reconstruction of detected Mg atoms in blue (b) Global concentration of Mg in doped layers in green and Mg concentration outside clusters and threading dislocation in black (c) Potential map including all the layers acquired at 400 °C in-situ heating temperature to increase the number of measured carriers (d) Potential profile across all the series of doped and undoped layers.