Nano-SIMS study of the spatial distribution of Mn ions in GaN

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Motivation:

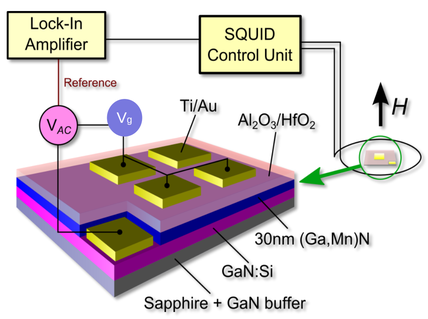
Here we investigate, dilute ferromagnetic insulator $Ga_{1-x}Mn_xN$, with x relating to the concentration of Mn ions substituting cation Ga sites. It is now well established that in uncompensated layers, the Mn ions are in 3+ charge state [1], and the Mn-Mn ferromagnetic superexchange interaction leads to Curie temperatures up to 10 K. Recently, we have shown that the magnitude and the sign of single Mn-ion magnetic anisotropy in GaN can be controlled by gate electric field [2]. In order to properly analyze the magnetic and magnetoelectric properties of this material, the spatial distribution of Mn ions in the GaN matrix should be carefully examined.

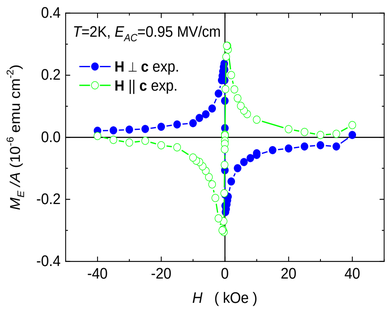
[1] W. Stefanowicz, D. S., et al., Physical Review B, 81, 235210 (2010)
[2] D. Sztenkiel, et al., Nature Communications 7, 13232, (2016)

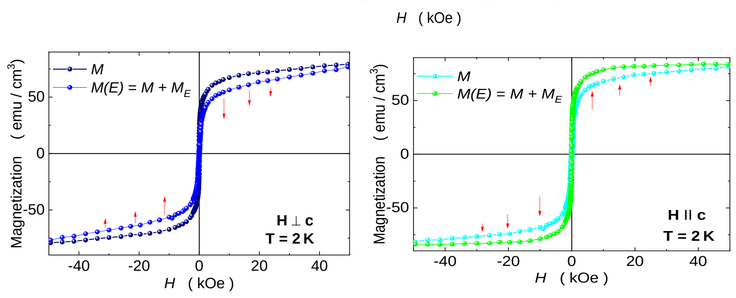
Conclusions

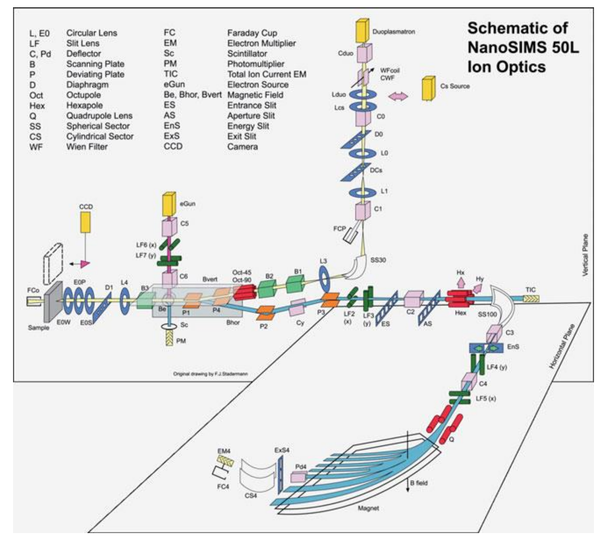
- Nanoscale secondary ion mass spectrometry (Nano-SIMS) investigation of the spatial distribution of Mn ions in GaN.
- In all $Ga_{1-x}Mn_xN$ films we detect traces of macroscopic inhomogeneities in the Mn concentration.

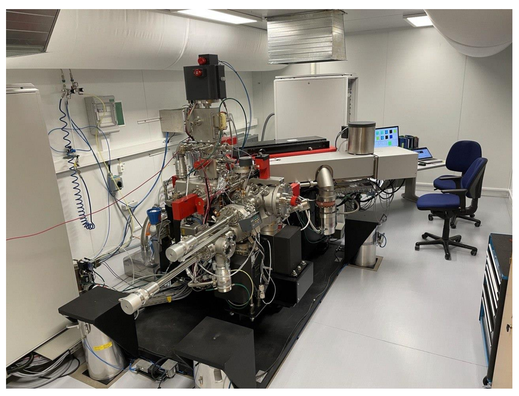
Why $Ga_{1-x}Mn_xN$ → magnetoelectric effect





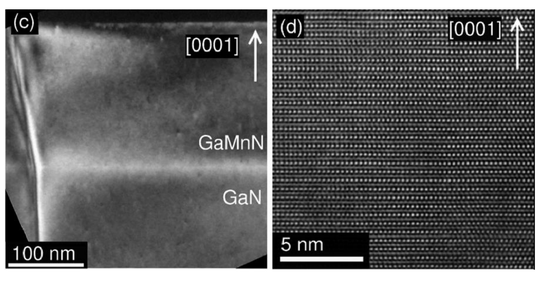




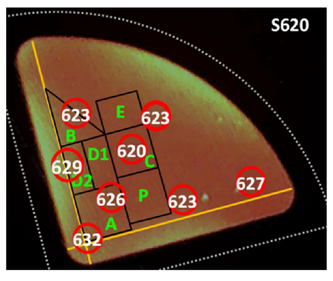


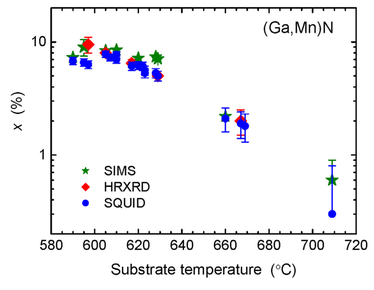
System under consideration – previous results

According to previous transmission electron microscopy (TEM), Rutherford backscattering and high-resolution x-ray diffraction results, Mn ions are homogeneously distributed over Ga-substitutional sites, without any precipitates or Mn-rich clusters [1, 2, 3, 4]. However, analysis of the critical exponents for $Ga_{1-x}Mn_xN$ layers indicates very small macroscopic inhomogeneities in the Mn concentration with a variance of Δx = 0.2% for samples with $x \simeq 10\%$ [5]. Moreover, a strong correlation of spatial Mn concentration with the actual (local) magnitudes of growth temperature across the substrate is also reported [4].



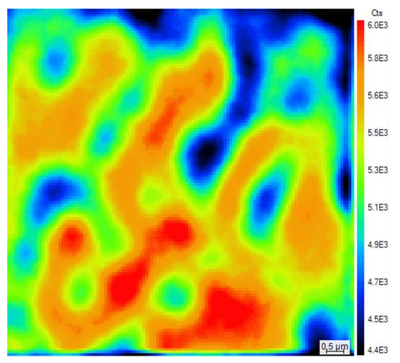
TEM : No evidence of crystallographic phase separation is detected for growth conditions close to the stoichiometric point.



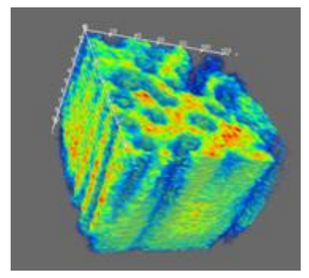


[3] G. Kunert, et al., *Appl. Phys. Lett.* 101, 022413 (2012)
[4] K. Gas, et al., Journal of Alloys and Compounds 747, 946 (2018)
[5] S. Stefanowicz, et al., Phys. Rev. B **88**, 081201(R) (2013)

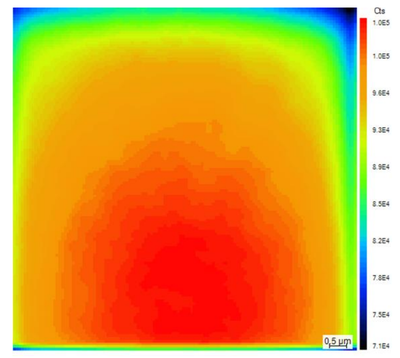
Nano-SIMS Concentration Maps



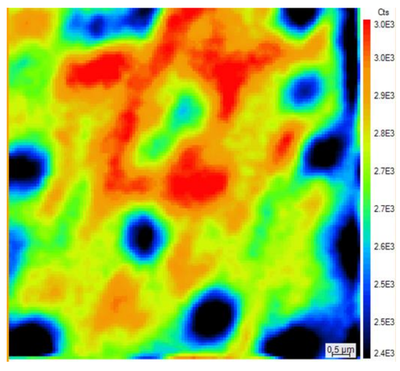
Mn



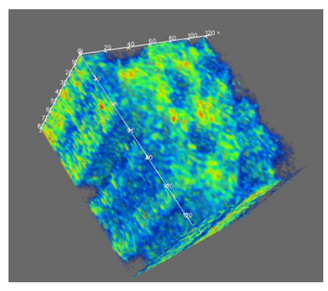
$Ga_{1-x}Mn_xN$, x=5%



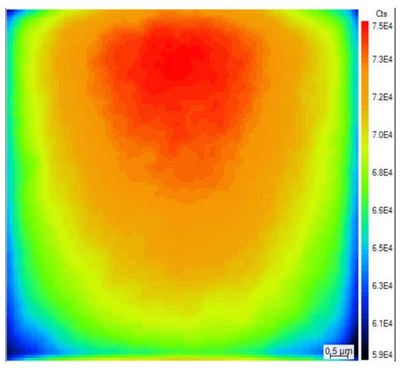
Ga



Mn



$Ga_{1-x}Mn_xN$, x=3%



Ga

A range of single-crystalline layers of $Ga_{1-x}Mn_xN$ with x ranging from 1.8% to 9%, grown by molecular beam epitaxy (MBE) are investigated by nanoscale secondary ion mass spectrometry (Nano-SIMS) at the chemical imaging infrastructure (CII), Gothenburg, Sweden. The Nano-SIMS allows precise elemental measurements with spatial resolution of about 50 nm. Importantly, in all $Ga_{1-x}Mn_xN$ films we detect traces of macroscopic inhomogeneities in the Mn concentration. An exemplary Mn concentration maps measured using Nano-SIMS are shown above.

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