Atom probe tomography of GaN vertical power diodes: impurity distribution near regrowth interfaces

A. S. Chang,[1] M. Nami,[2] B. Li,[2] J. Han,[2] and L. J. Lauhon[1]
[1] *Department of Materials Science and Engineering, Northwestern University, Evanston, IL, USA*
[2] *Department of Electrical Engineering, Yale University, New Haven, CT, USA*

GaN has demonstrated its utility in lighting and RF application and are being considered as the next generations of vertical power devices. However, high leakage currents, current crowding followed by premature breakdown, and degradation of the device[1] have hindered the GaN technology from entering the market. For nonplanar vertical power diodes, active regions of the device are formed through ex-situ processes, e.g. regrowth and selective area growth. Therefore, precise control of intentional and unintentional impurity incorporation near these interfaces is essential for achieving high performance devices[2]. Analysis of the 3D spatial distribution and concentration of solute impurity atoms can be difficult, especially for nonplanar interfaces; thus, tomographic analysis becomes necessary. We describe atom probe tomography (APT) characterization of planar n/n and p/n GaN homojunctions with emphasis on detection sensitivity of dopants.

GaN homojunctions were grown by metal-organic chemical vapor deposition at Yale University, and analyzed using APT at Northwestern University. n-GaN templates were exposed to air prior to the regrowth of n-GaN or p-GaN to test subsequent cleaning procedures, and APT detection limits for impurities in GaN substrates and planar regrowth were analyzed by comparison with secondary ion mass spectroscopy (SIMS). Si impurities were observed with a surface density of 10^{12}cm^{-2} for both n/n and p/n homojunctions and attributed to contamination from reactor parts and air. However, detection of Si in GaN using APT was limited due to the overlapping $^{28}Si^{+}$ and $^{14}N_2^{+}$ mass to charge ratios. The detection limits of other intentional and unintentional impurities in APT varied from 10^{17}cm^{-3} to 10^{19}cm^{-3}, depending on the peak positions relative to the Ga and N ion thermal tails. Analysis on spatial distribution of p-type dopant atoms did not reveal any evidence of clustering. Within the reconstructed APT data, the location of the regrowth interface of n/n homojunction was identified by spatial variations in charge states of evaporated Ga ions (Ga CSR). Although noticeable fluctuations in Ga CSR also coincided with the p/n homojunction, no clear correlation between Ga CSR and Mg concentration was observed. We will discuss efforts to extract the built-in field near p/n junctions and correlate with dopant concentrations.

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[2] I.C. Kizilyalli, P. Bui-Quang, D. Disney, H. Bhatia, and O. Aktas, *Microelectronics Reliability* **55**, 1654-1661 (2015).

[+] Author for correspondence: lauhon@northwestern.edu

Supplementary Pages

Atom	Noise floor in GaN APT	Limiting factor
Ge (dopant)	2×10^{19} cm^{-3}	Ga^{++} overlap
Mg (dopant)	$0.2\text{-}2 \times 10^{18}$ cm^{-3}	C^{+} overlap
Si (dopant or impurity)	-	N_2 overlap
O (impurity)	1×10^{19} cm^{-3}	N related peaks
C (impurity)	5×10^{18} cm^{-3}	Uncorrelated evaporation

Table 1. Summary of measured detection limits for impurities of interest from mass spectra of typical APT runs on GaN. The limiting factor for noise levels of each impurity is described. APT data were collected in pulsed laser mode at 250 kHz and pulse energies of 10 fJ at an evaporation rate of 1 ion detection / 500 pulses.

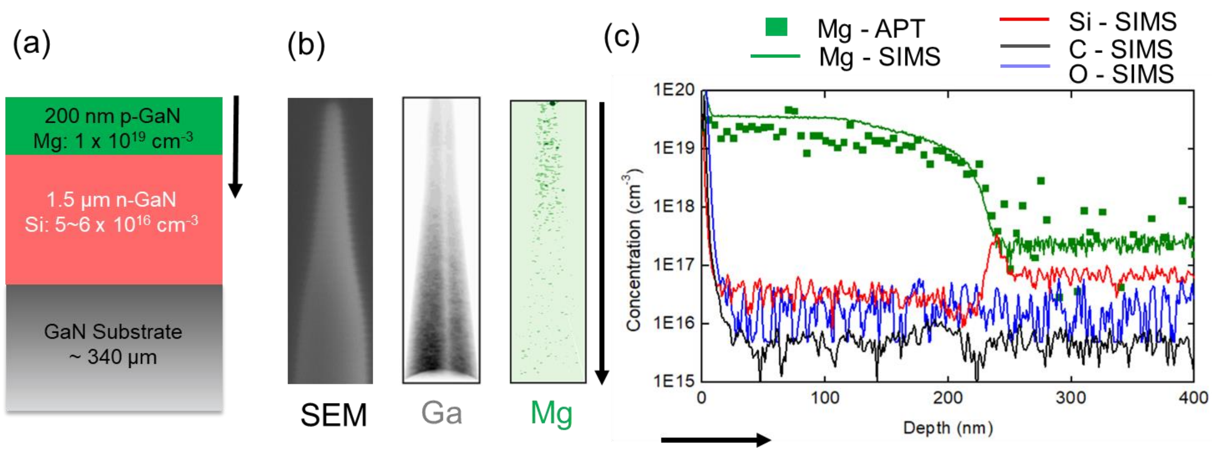

Figure 1. (a) Sample diagram of p/n GaN heterostructure. (b) (left) SEM image of focused-ion beam prepared APT specimen in comparison to (middle) Ga and (right) Mg contour plot generated from reconstructed APT data. (c) Concentration profile along the c-axis from APT (symbol) and SIMS (line) data. The Mg concentration of APT and SIMS agree well, with a higher background level of x_{Mg} for APT than SIMS. x_O and x_C levels in SIMS were below the detection limit of APT data.

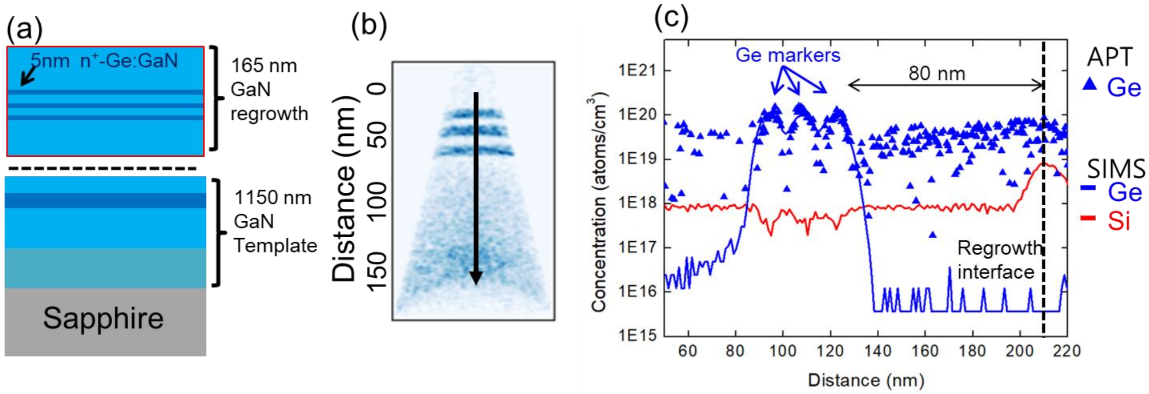

Figure 2. (a) Sample diagram of n/n GaN heterostructure. 5 nm, highly doped Ge:GaN layers were utilized as marker layers. (b) Ge contour plot generated from reconstructed APT data. (c) concentration profile along the c-axis from APT (symbol) and SIMS (line) data. The high background level of x_{Ge} in APT is due to the large tail of Ga peaks overlapping with Ge peaks in the mass spectra.

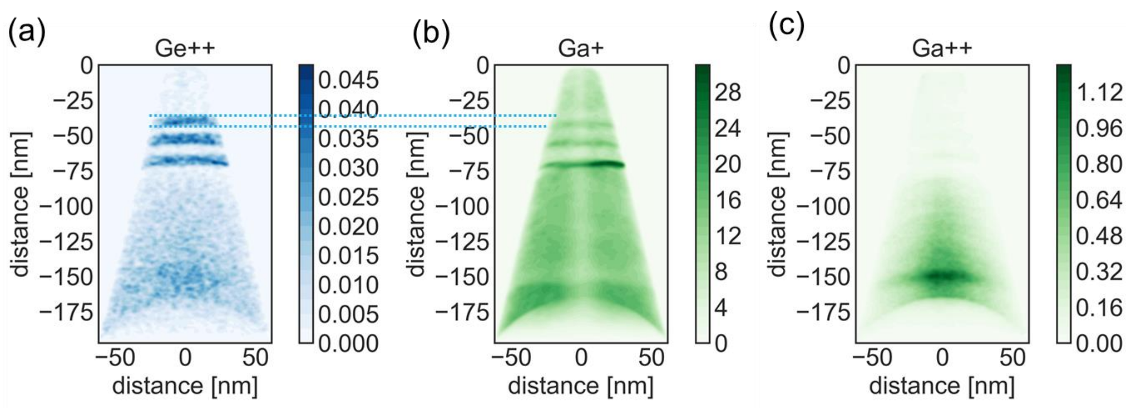

Figure 3. (a) Ge^{+}, (b) Ga^{+}, and (c) Ga^{++} contour plots generated from reconstructed APT data on n/n test structure. A higher hit density of Ga^{+} ions is observed when evaporating from Ge:GaN to Si:GaN. A high hit density of Ga^{++} ions is observed near the regrowth interface, which from SIMS studies is known to be Si doped.