Multicharacterization approach for studying InAl(Ga)N/Al(Ga)N/GaN heterostructures for high electron mobility transistors

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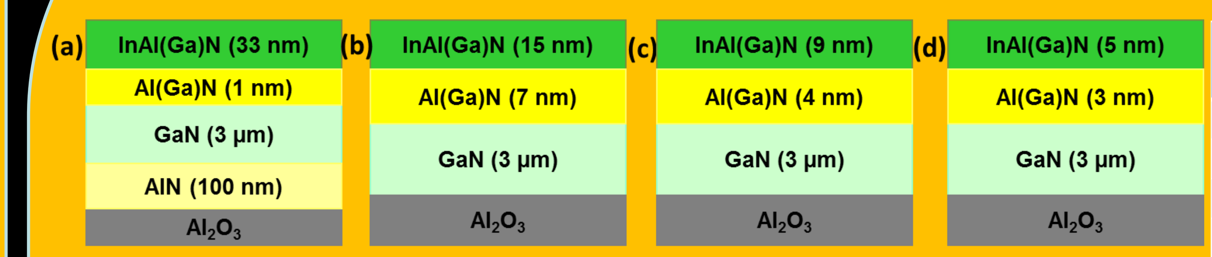
Motivation

- InAlN is an attractive candidate for high frequency transistor applications and InAlN can also be lattice matched with GaN when the In composition is ≈ 18% which makes it a strong contender for high electron mobility transistors (HEMTs) [1].
- The production of high quality InAlN/GaN HEMTs faces many growth challenges such as phase separation, composition fluctuations and even growth disruption. Recently unintentional Ga incorporation in the InAlN layers has been reported which adds to the list of growth challenges of InAlN thin films [2].
- The objective of this work is to use a multi–pronged approach to understand the structural, compositional and electrical properties of InAlN(barrier)/AlN(Interlayer)/GaN HEMT structures (where Ga has been unintentionally incorporated in both the barrier and interlayer) using various characterization techniques. We will also discuss the role of unintentional Ga incorporation on the 2-DEG properties.

Experimental details



Samples	AlN T_{growth} (°C)	InAlN T_{growth} (°C)	AlN P_{growth} (m bar)	InAlN P_{growth} (m bar)	V–III ratio
A	790	790	70	70	5000
B	790	790	70	70	5000
C	1200	865	50	70	2200
D	1200	865	50	70	2200

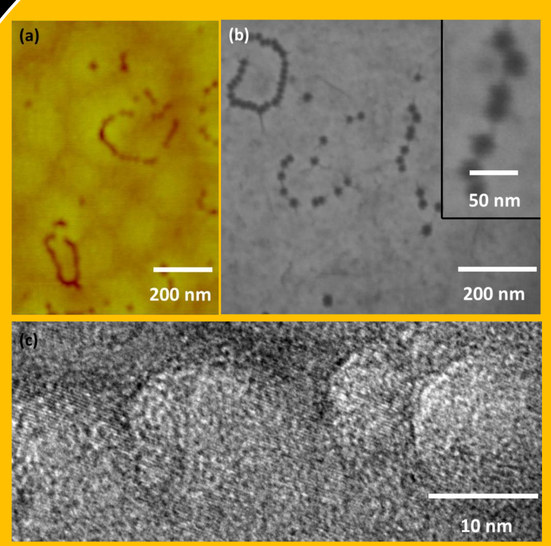
Schematic of the HEMT structures and growth conditions: (a) sample–A and (b) sample–B were grown in the Aixtron 3 × 2 inch close coupled showerhead reactor (c) Sample–C and (d) sample–D were grown in the Aixtron 200 RF horizontal reactor.

For the sake of clarity most of the results and discussion will focus only on **"sample–A"**. Samples (B–D) were used to demonstrate the unintentional Ga incorporation both in the barrier and in the interlayer for the two different reactor designs.

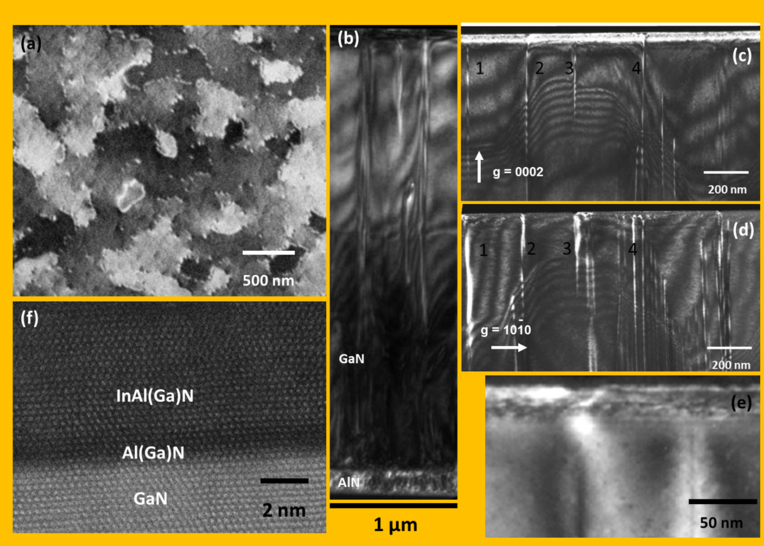
Characterization techniques used in this work

- Atomic force microscope **(AFM)**, tapping mode **-** topography and surface roughness
- Scanning electron microscope **(SEM)**, secondary electron (SE) images at 30 keV - surface morphology
- Electron channelling contrast imaging **(ECCI)** at 30 keV - grain boundaries and structural defects
- Transmission electron microscope **(TEM)** and aberration corrected **STEM** high angle annular dark field (HAADF) imaging at 200 keV - structure thicknesses, defects and composition of the interfaces
- Energy dispersive X–ray spectroscopy **(EDX)** in a STEM - nanoscale compositional analysis
- High resolution X–ray diffraction **(HRXRD)** using an X'Pert MRD triple axis diffractometer equipped with a Ge monochromator operating at the Cu $K_{\alpha 1}$ wavelength of 1.54056 Å, Rutherford backscattering spectrometry in the channelling geometry **(RBS/C)** using a 1.6 MeV $^{4}He^{+}$ beam and X–ray photoelectron spectroscopy **(XPS)** with a monochromated Al K_{α} ($h\nu$ = 1486.9 eV) radiation as an X–ray source **-** compositional analysis
- Room temperature (R–T) **Hall measurements** performed in the Van der Pauw geometry and capacitance–voltage **(C–V) measurements** at R–T were performed using Ti/Al/Ni/Au based ohmic contacts (dots of 0.6 mm diameter) and Ni/Au Schottky diode contacts (dots of 1 mm diameter) at an operating frequency of 1 KHz. **-** 2–DEG related properties
- 1–D Poisson–Schrödinger **simulations of band diagrams** for HEMT structures with and without Ga in the barrier and interlayer by using nextnano simulation software.

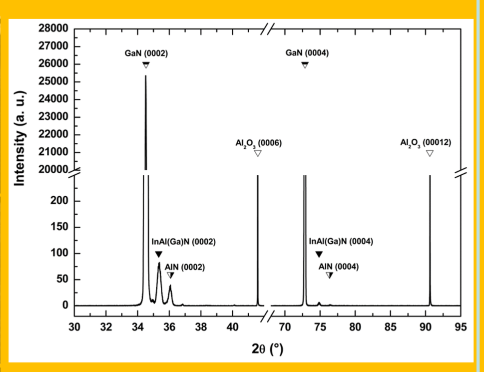
Results and discussion



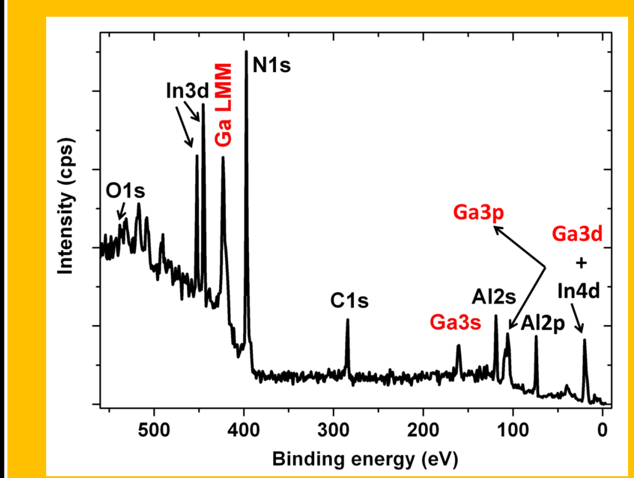
(a) AFM, (b) plan view SE and (c) plan view TEM images showing individual and clustering of V–defects.



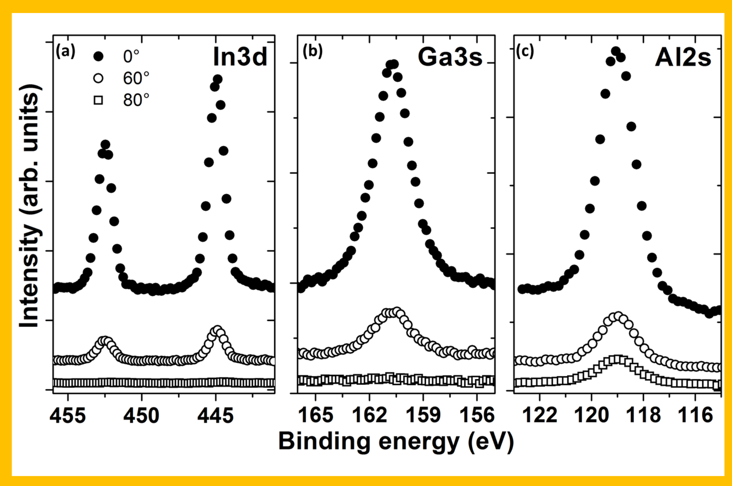
(a) ECCI showing V–defects decorating the grain boundaries (b & c) 2–beam dark field image (0002 reflection) (d) 10-10 reflection showing TDs propagating to the surface and connected to V–defects (e) TD which is not connected to a V-defect (f) HAADF image revealing smooth interfaces



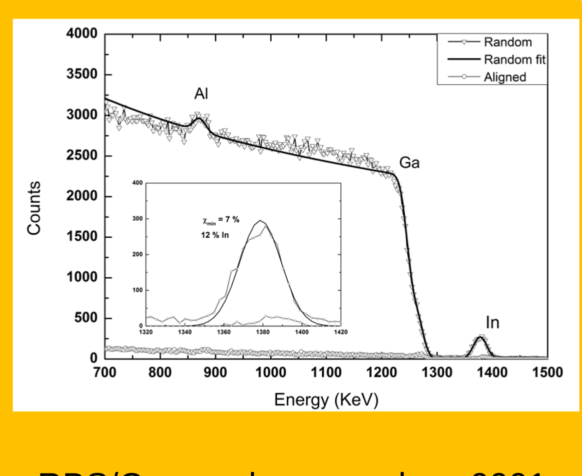
HRXRD θ-2θ diagram of InAl(Ga)N/Al(Ga)N/GaN/AlN on Al_2O_3 substrate, the c–plane lattice constant was found to be 0.507 nm



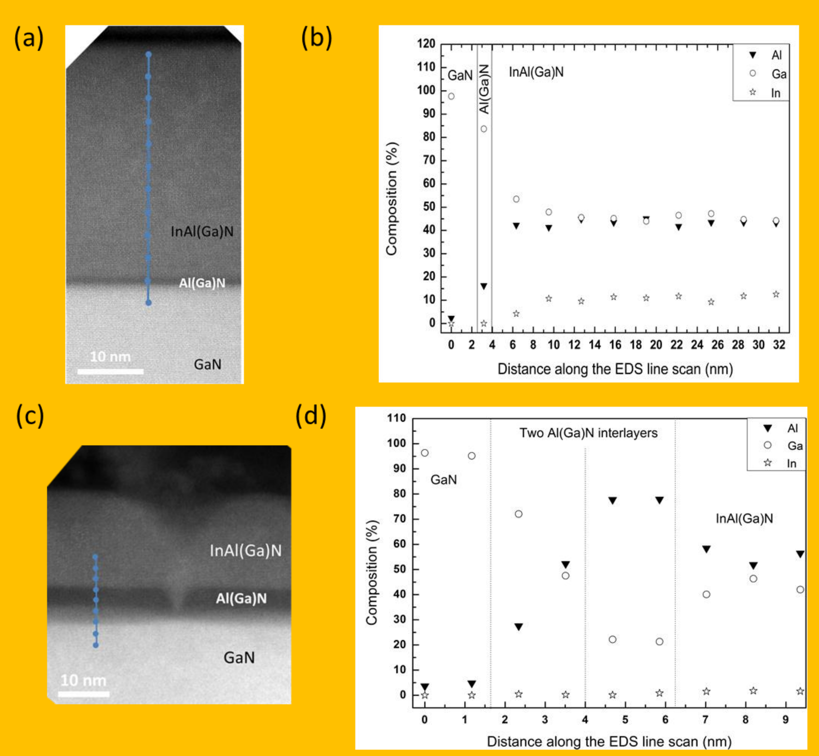
XPS spectrum from the barrier layer after annealing at 650°C under UHV conditions. The core-level peaks are labelled corresponding to their electronic states.



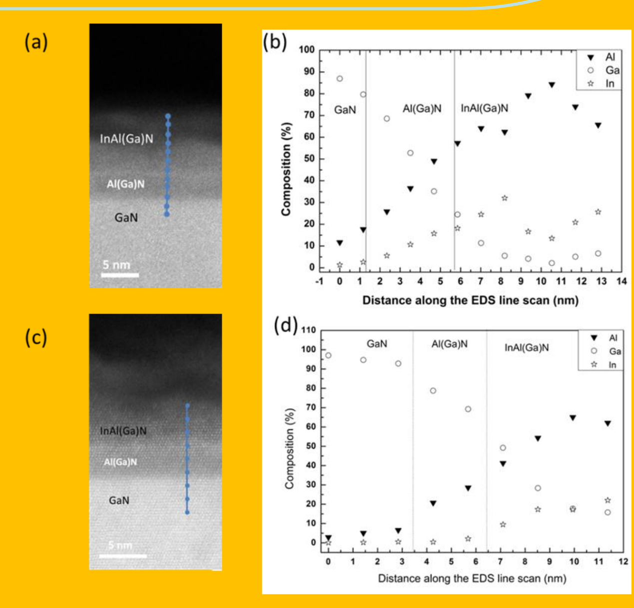
The XPS core-level spectra: a) In 3d, b) Ga 3s, c) Al 2s recorded at take-off angles of 0°, 60° and 80° respectively after annealing at 650°C.



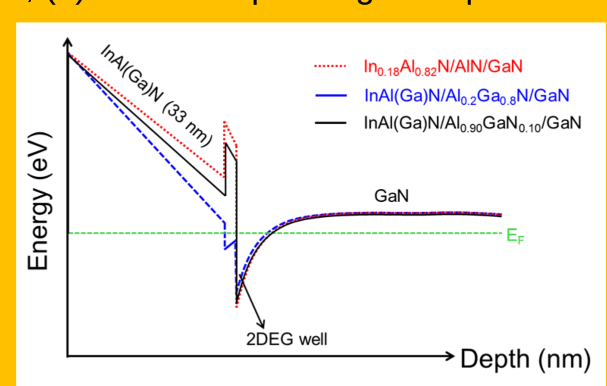
RBS/C random and <0001> aligned spectra, the inset image shows the spectra for the In signal in the 1360-1400 keV energy range in the RBS spectrum whereas the Al signal is at 855-890 keV and the Ga signal at 1270 keV.



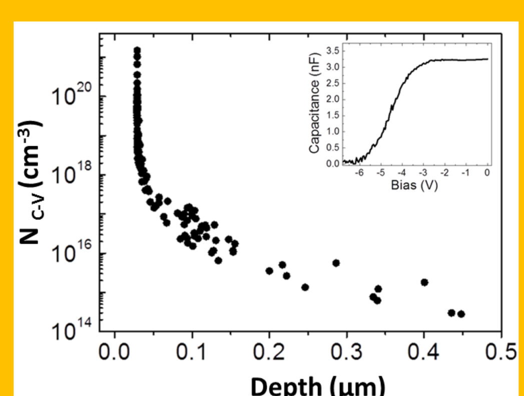
Samples grown in a showerhead MOVPE reactor: (a) Cross section HAADF-STEM image, the dotted line shows the position of the EDX line scan of sample-A across the heterostructure, (b) the corresponding EDX profiles showing the Al, Ga and In composition as a function of position, (c) HAADF-STEM image of sample-B, (d) the corresponding EDX profiles



Samples grown in a horizontal MOVPE reactor:(a & c) Cross section HAADF-STEM of sample-C & D respectively, (b & d) their corresponding EDX profiles



Schematic representation of the simulated band diagrams for heterostructures with high/low Ga diffusion in barrier and interlayer



Free carrier concentration against depth showing the sharp increase related to the presence of the 2-DEG at the InAl(Ga)N/Al(Ga)GaN interface. The C-V profile shown in the inset evidences the depletion of the 2-DEG.

Results summary for sample–A

	AFM	SEM	ECCI	TEM
Surface Roughness (nm) (for a 5 µm × 5 µm area)	0.8	-	-	-
Defect density (x 10^9 cm^{-2})	0.8 (V-defects only)	3 (V-defects only)	5 (Total)	3 (Total)

	HRXRD	RBS	XPS	TEM-EDX
In content %	13 (assuming no Ga is present in the barrier layer)	12	7 (bulk barrier) 1 (at surface of barrier layer)	11 (10 nm from interface between interlayer and barrier)
Al content %		56	70 (bulk barrier) 93 (at surface of barrier layer)	45 (10 nm from interface between interlayer and barrier)
Ga content %		32	25 (bulk barrier) 6 (at surface of barrier layer)	44 (10 nm from interface between interlayer and barrier)

- The interlayer shows an Al content of 36% and a Ga content of 84%.
- The 2–DEG density value was found to be ≈ 3 x 10^{13} cm^{-2}, the R–T Hall mobility is ≈ 980 cm^2/V-s and the sheet resistance is ≈ 210 Ohm/sq.
- The background carrier concentration related to the GaN layer was estimated to be of the order of 10^{16} cm^{-3} using the method proposed in reference [3].
- Simulated band diagrams, assuming high Ga content in the barrier and interlayer (80%), show the presence of a second well in parallel to the main 2–DEG well.
- The existence of this narrow, weak parallel well may be due to a very small band offset between barrier layer and interlayer, which bends the conduction band below the Fermi level at the InAl(Ga)N/Al(Ga)N interface.
- The origin of unintentional Ga is believed to be from the surrounding surfaces in the growth chamber and from the wafer susceptor.
- Interrupting the growth and cleaning the reactor prior to growing the interlayer and barrier may be a route to reduce the unintentional Ga incorporation as described by Hiroki et al [4].
  - Future work is necessary to understand the role of reactor designs to reduce/eliminate unintentional Ga incorporation.

Summary and conclusions

- The presence of unintentional Ga in the barrier as well as in the interlayer for samples grown using both showerhead and horizontal MOVPE reactors is reported.
- The existence of unintentional Ga in the HEMT structures does not appreciably affect the 2–DEG properties; however it could be a problem during device processing.
- Producing a HEMT structure with InAlGaN as a barrier and AlGaN as an interlayer, with appropriate alloy composition, may be a possible route to optimization as it might be difficult to avoid Ga incorporation while continuously depositing the layers using the MOVPE growth method.

References

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