

Development of GaN-on-Ga₂O₃ Heterostructures for Vertical Power Devices

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Abstract

For the development of gallium oxide (Ga₂O₃) as a power electronics platform, a method of forming p-n junctions is required. Here, the feasibility of gallium nitride (GaN)-on-Ga₂O₃ p-n heterojunctions is discussed, as enabled by nitridation of Ga₂O₃ and subsequent GaN epitaxy via plasma-assisted molecular beam epitaxy (PAMBE). Key materials and electrical characterization methods are explored for such films and initial data is presented.

INTRODUCTION

The power electronics industry is ever-growing and relies on the ability to make highly efficient power devices for switching applications. With this in mind, β-Ga₂O₃ is a material that has attracted interest owing to its high critical electric field, ultra-wide band gap, moderate n-type mobility, and the relative ease of bulk crystal growth [1]. Baliga's figure of merit for power switching applications puts Ga₂O₃ several times above gallium nitride (GaN) and silicon carbide, two of the current dominant material systems for power devices [1]. However, Ga₂O₃ has its share of challenges. The main obstacle which we attempt to address here is the difficulty of p-type doping in Ga₂O₃. As p-n junctions are essential to many power switching devices, being able to produce such a junction is imperative if Ga₂O₃ is to become a major material platform in this industry.

There are two key challenges to p-doping: the lack of suitable shallow acceptors and a very high hole effective mass [2]. Due to these challenges being inherent to the material itself, no known success has been demonstrated for p-doping through traditional methods. For this reason, much effort has been put into finding materials that can be p-doped and used to form heterostructures with Ga₂O₃. While many materials have been tried, GaN is an attractive option owing to it already being a relatively developed power electronics platform and its low lattice mismatch with Ga₂O₃ [3]. Additionally, via nitridation Ga₂O₃ can be converted into GaN providing a suitable buffer layer for subsequent epitaxy.

Some work has been done in this area already with limited success. Two main methods have been used which are ammonia-based and nitrogen-plasma-based. Ammonia nitridation has been shown to create significant surface pitting due to reaction between hydrogen and oxygen in the Ga₂O₃

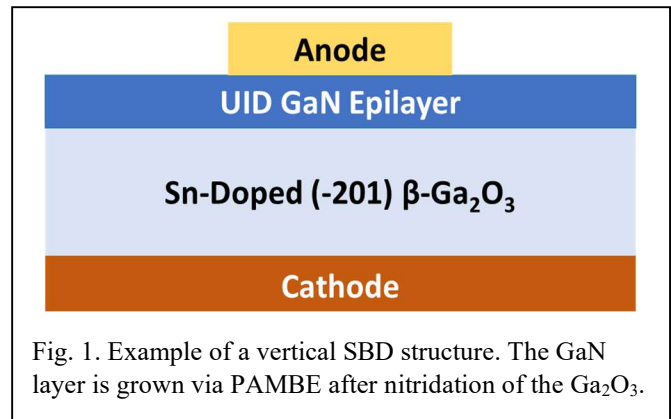


Fig. 1. Example of a vertical SBD structure. The GaN layer is grown via PAMBE after nitridation of the Ga₂O₃.

surface [4]. Nitrogen-plasma nitridation has been used to create buffer layers for subsequent growth in PAMBE. This method has had some success but has not been explored sufficiently, with little quantitative discussion and even less elucidation of the mechanism of nitridation [5]. In this work, we further investigate this method from both experimental and theoretical approaches to evaluate its effectiveness. More specifically, we evaluate the capability of properly treated nitridation to enable subsequent epitaxy of p-type GaN on Ga₂O₃ which has not yet been demonstrated to the authors' knowledge.

To make this evaluation, we must establish certain metrics by which to judge the quality of our GaN films. The main characterization methods we will use to do this are x-ray diffraction (XRD), photoluminescence (PL), current-voltage measurements (I-V), and capacitance-voltage measurements (C-V). For XRD, we aim for a rocking curve full width at half maximum (FWHM) of ~300arcsec indicating termination of dislocations as well as strain relaxation within our nitridated film. For PL, we aim for little to no emission within the GaN band gap indicating an absence of defect states that would inhibit effective dopant activation or result in dopant compensation. For I-V, vertical Schottky barrier diodes (SBDs) will be produced, making ohmic contact to the n-type Ga₂O₃ substrate and Schottky contact to the undoped GaN films. Highly rectifying behavior is desired. A diagram of the device structure is shown in Fig. 1. With these same devices we will do C-V measurements to determine carrier concentration, aiming to maintain unintentional doping (UID) levels below 10¹⁷cm⁻³ throughout the GaN film.

Experimentally, (-201)-oriented tin-doped β-Ga₂O₃ substrates are used for minimal lattice mismatch. The samples

are cleaned ex-situ with organic solvents and acids before being loaded into the PAMBE system. Samples are then heated to desorb any residue before being cooled to the nitridation temperature. Nitridation variables are substrate temperature, nitridation time, and nitrogen plasma conditions. Surface configuration is monitored via reflection high-energy electron diffraction (RHEED). Details of the nitridation process can be found in our sister paper [M. M. Landi, Characterization of Nitridated Ga₂O₃ for GaN-on-Ga₂O₃ Power Device Applications, Paper #15.4]. Post-nitridation, the substrate temperature is raised to grow a UID GaN film, the conditions for which are fixed. In some cases, the samples are removed for characterization prior to growth and are re-cleaned as previously described. XRD studies are done on a Bruker D8 Advance and PL studies are done with a custom setup using 266nm 4mW excitation at 77K and 300K. Schottky contacts were made by cleaning the substrates with piranha, performing standard photolithography to define contact area, a 1min BOE surface clean, 30/100nm Pt/Au deposition, and a 5min contact anneal at 500°C. A thin SiO₂ layer was deposited on the surface for passivation. A 20/100nm Ti/Au non-annealed blanket ohmic contact was deposited on the back side of the substrate.

XRD data collected so far have begun to elucidate some of the processing difficulties that can arise by improper treatment of the nitridation process. Due to a desire to characterize directly the nitridated layers, many early films were removed from the PAMBE system and subsequently re-cleaned both ex-situ and in-situ. As growths progressed, it was observed that this process resulted in a degradation of the films. Initially it was believed that the secondary cleaning process was removing part of the nitridated GaN film. To combat this, a lighter cleaning process was employed, however, it was determined that this method was not removing the native oxide formed on the nitridated GaN surface. There were additionally concerns of misalignment to the nitridated region of the sample upon reintroduction to the system. Lastly, it was discovered that the optimal growth conditions for GaN on Ga₂O₃ require slightly more gallium initially resulting in some of the films being partially nitrogen rich, thus degrading them. The results of this can be seen in Figure 2. From the plot, the samples with remaining native oxide were the worst, followed by samples having been removed from the MBE but with the oxide fully removed. Nitrogen-rich conditions uniformly worsened the films, presumably due to a lack of a Ga wetting layer that would allow for more strain relaxation at the interface. The samples that were not removed from the MBE at all showed the best performance with a recent sample having a FWHM of 189.9arcsec. To the authors' knowledge, this is far below the previous record for GaN on Ga₂O₃, which was achieved by metal-organic chemical vapor deposition (MOCVD) (330arcsec) [6]. While it is noted that crystallinity improvement plateaus beyond 10nm of thickness, it is expected that growth conditions can be further optimized, specifically by controlling the Ga/N-ratio throughout the growth.

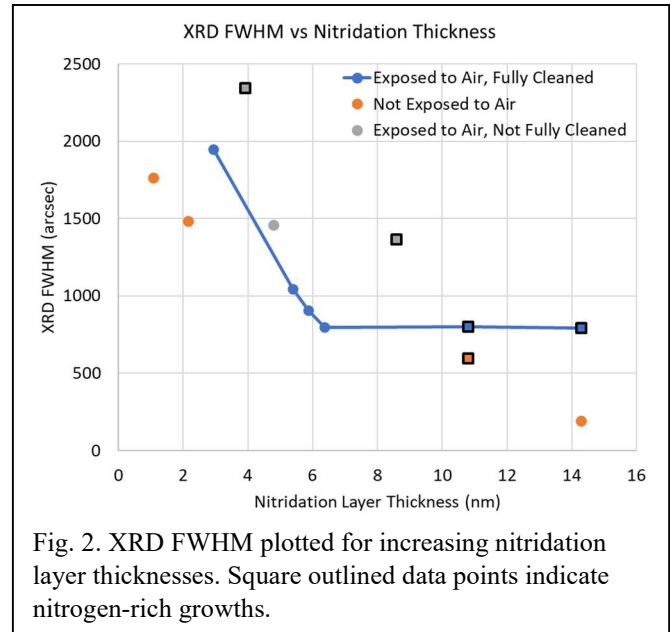


Fig. 2. XRD FWHM plotted for increasing nitridation layer thicknesses. Square outlined data points indicate nitrogen-rich growths.

Photoluminescence spectra were obtained for the films at high and low temperatures. Figure 3 shows representative spectra of GaN on Ga₂O₃ films measured at room temperature (300K) and at liquid nitrogen temperature (77K). There are 3 main features present in the spectra: near band-edge emission which shifts from 3.467eV to 3.412eV with increasing temperature, ultraviolet (UV) emission which shifts from 3.260eV to 3.336eV with increasing temperature, and yellow emission located at 2.209eV which does not vary with temperature. The near band-edge emission is regularly attributed to an acceptor-bound exciton. The sharp UV lines seen at low temperature are attributed to C_N acceptors; in some cases, these lines are attributed to Mg incorporation, however, there is no evidence in our films that Mg could be incorporated to demonstrate the trends seen. Therefore, carbon contamination must be responsible for the UV luminescence. Lastly, there is the yellow band, the source of which is heavily debated. Generally, it is either attributed to carbon contamination or V_{Ga}O_N complexes. Both of these are distinct possibilities as the prevalence of the UV band suggests carbon contamination and the substrate allowing for oxygen in-diffusion could assist in generating the complex. It is also highly possible that a combination of these two effects is at work. For samples that were removed from the MBE and fully cleaned, a trend is visible that greater surface roughness contributes to a lessening of the yellow line intensity relative to the near band-edge intensity. This could indicate a reduction in the in-diffusion of oxygen with greater amounts of ion bombardment. [7]

After device fabrication, I-V measurements were done to investigate the rectifying behavior of the devices. All measured devices showed rectifying behavior, however, with very low on/off ratios (10-100, measured at 2V). To further investigate this, the I-V curves were used to determine the

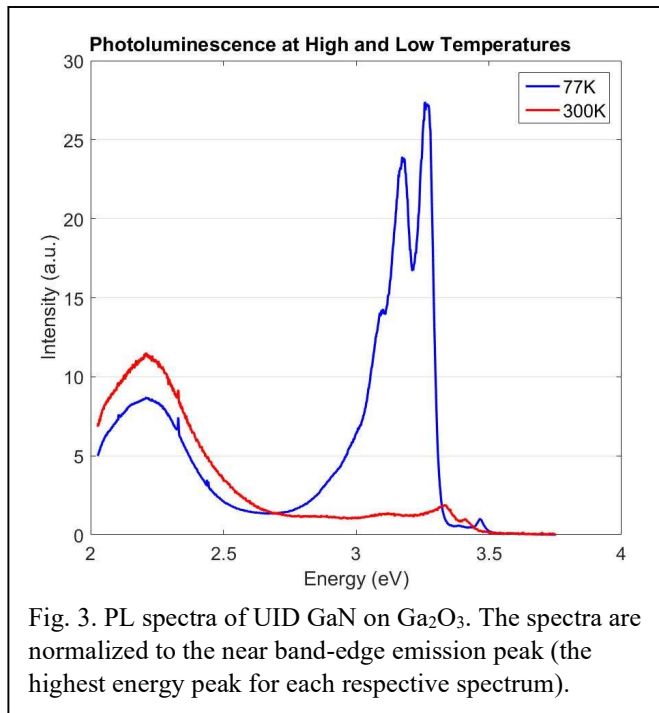


Fig. 3. PL spectra of UID GaN on Ga₂O₃. The spectra are normalized to the near band-edge emission peak (the highest energy peak for each respective spectrum).

Schottky barrier height. The natural log of the derivative of the following equation for thermionic emission current was used:

$$I = AA^{**}T^2 e^{\frac{-\Phi}{kT}} (e^{\frac{qV}{kT}} - 1)$$

Taking the y-intercept, the barrier height, Φ , can be solved for. For all devices, the barrier was pinned to approximately 0.5eV. The source of the Fermi-level pinning is as of yet unknown, though it was observed that a lateral GaN on GaN device processed at the same time did not undergo pinning. Therefore, it must be due to defects present only in the GaN on Ga₂O₃ films. More specifically, either defects identified in the previous paragraph, higher dislocation densities in the films, or a combination could create surface states pinning the Fermi level. Additionally, a short anneal partially unpinned one device, raising its barrier to 0.58eV. Notably this was one of the films not removed from the MBE and not nitrogen-rich.

C-V studies were performed on the devices at varying frequencies. 1MHz measurements were used as the baseline for comparison across samples. An example of the fitting is shown in Figure 4. In general, unintentional doping concentrations were in the range of 1×10^{16} - 3×10^{17} cm⁻³. Some samples showed higher concentrations at lower frequencies, indicating mobile charge carriers. So far there is not an apparent correlation between the few samples that showed this and the growth conditions. Depth profiling via C-V showed that most samples were uniformly doped, though it is expected that data for this can be improved by resolving the Fermi-level pinning. The overall doping levels can be expected to be improved as UID-GaN on GaN growths have had carrier concentrations of 5×10^{15} cm⁻³.

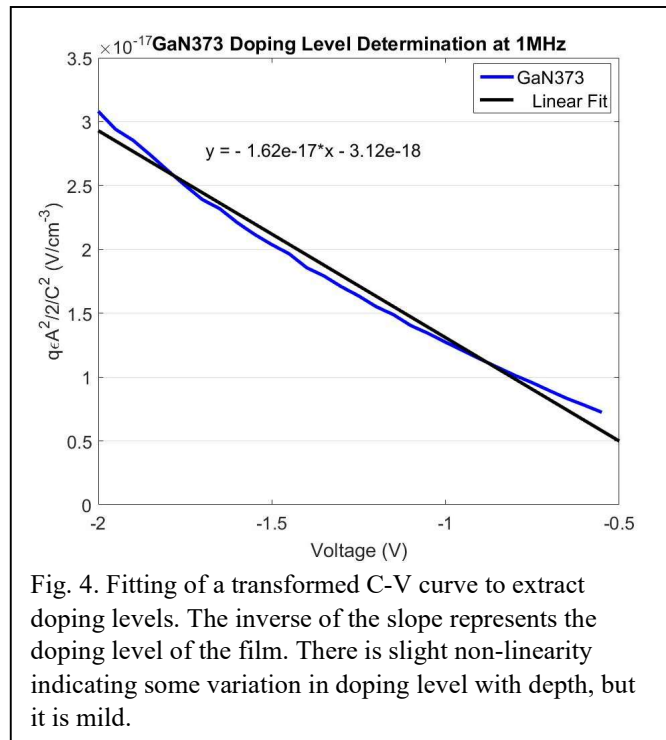


Fig. 4. Fitting of a transformed C-V curve to extract doping levels. The inverse of the slope represents the doping level of the film. There is slight non-linearity indicating some variation in doping level with depth, but it is mild.

CONCLUSIONS

Initial work into improving the crystallinity of GaN films grown on Ga₂O₃ has been promising. Further investigation is underway to optimize GaN on Ga₂O₃ growth, enabling high-power devices and p-doped GaN on Ga₂O₃. XRD studies have helped to determine a necessary thickness for high crystallinity materials growth. PL measurements have assisted in identifying key defects inhibiting high-performance devices. I-V and C-V measurements have confirmed the presence of defects pinning the Fermi level and elevating carrier concentrations. Current work is focused on identifying the source of these defects and eliminating them to produce high-performing devices.

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ACRONYMS

Ga₂O₃: Gallium Oxide
GaN: Gallium Nitride
PAMBE: Plasma-Assisted Molecular Beam Epitaxy
XRD: X-ray Diffraction
PL: Photoluminescence
I-V: Current-Voltage
C-V: Capacitance-Voltage
FWHM: Full Width at Half Maximum
SBD: Schottky Barrier Diode
UID: Unintentional Doping
RHEED: Reflection High-Energy Electron Diffraction
MOCVD: Metal-Organic Chemical Vapor Deposition
UV: Ultraviolet