Mobility of the Two-Dimensional-Electron-Gas in Lattice-Matched InAlN/GaN Grown by Ammonia Molecular Beam Epitaxy

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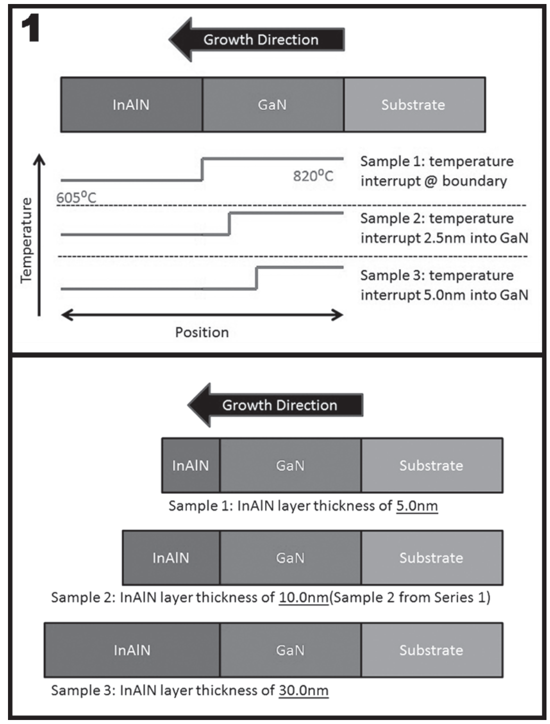
Introduction:

Transistors are components on electronic boards that amplify signals and power and relay these to the rest of the electronics board. A novel model of a transistor is the high electron mobility transistors (HEMTs), which has several advantages over other transistors: high power per unit width, high frequency, high voltage operation, and low noise [1]. HEMTs operation occurs from the modulation of a two-dimensional-electron-gas (2DEG). The 2DEG channel is created at the interface of two different materials where the conduction band bends below the Fermi-level. In this channel, the material acts like a metal, hence a high mobility. The $In_{0.18}Al_{0.82}N$/GaN material, abbreviated InAlN/GaN, has great potential as a HEMT. One reason is that the material is lattice matched — meaning there is no internal strain [2]. Despite this, growing the bi-material system is difficult because InAlN must be grown at lower temperatures than GaN for In incorporation, typically resulting in poor material quality [3].

A method of growing InAlN/GaN is using molecular beam epitaxy (MBE); conventionally, plasma-assisted MBE using pure nitrogen is used, whereas using ammonia as the nitrogen source is less thoroughly studied. However, ammonia-MBE has potential due to higher achievable growth temperatures and a nitrogen-rich environment. This project studied the effects of the growth-temperature-interrupt-depth and InAlN-layer thickness on electrical properties.

Experimental Procedure:

Samples were grown using molecular-beam-epitaxy (MBE) which uses high temperatures and low pressures to sublime gallium (Ga), aluminum (Al), and indium (In) metal targets onto a substrate and simultaneously flowing ammonia (NH_3) to grow the InAlN/GaN layers. Two series were grown: the first to optimize the growth-temperature-interrupt-depth (GTID), and a second series was grown to optimize the InAlN-layer thickness (See Figure 1). All samples had a very thin 1 nm layer of AlN at the InAlN/GaN interface to improve the mobility [3]. All samples from Series-1 had an arbitrary InAlN thickness of 10 nm, and the samples from Series-2 (dependent on electrical results from Series-1) had a GTID of 2.5 nm. The Series-2 sample with an InAlN thickness of 10 nm was the same sample from Series-1 with a GTID of 2.5 nm. A photolithography procedure was used to pattern parts of the sample for electrical measurements (See Figure 2).



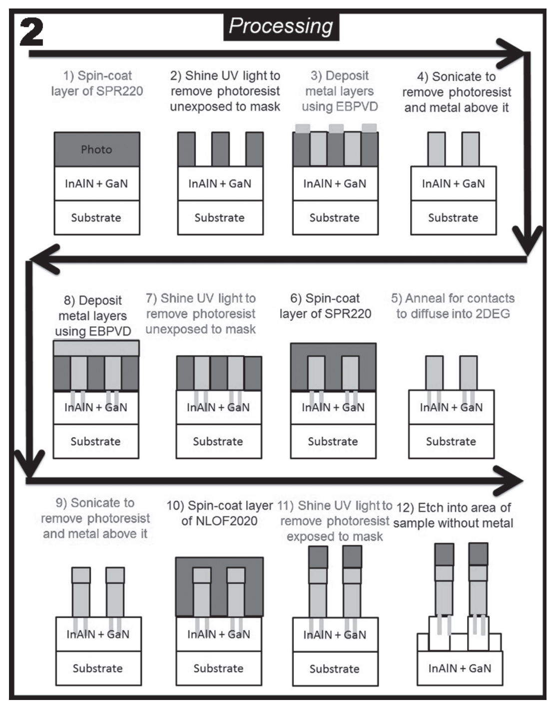


Figure 1, top: (a) Series-1 variation of growth-temperature-interrupt-depth. (b) Series-2 variation of InAlN thickness.

Figure 2, bottom: Overview of photolithography procedure, including before and after images, process flow chart, and Hall/TLM patterns.

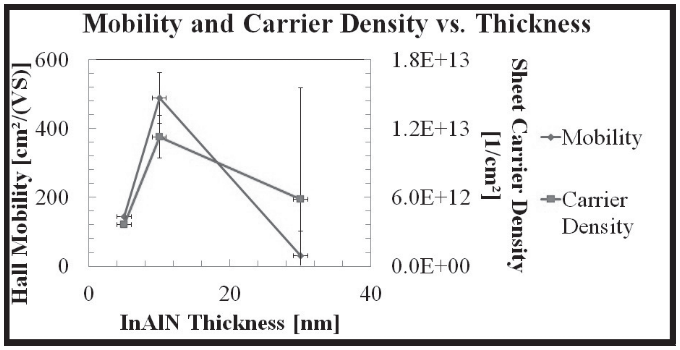


Figure 3: Series-2 mobility (blue) and carrier density (red) dependence on InAlN thickness.

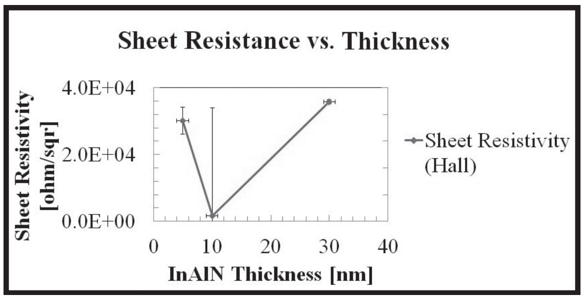


Figure 4: Series-2 sheet resistance dependence on InAlN thickness.

Results and Conclusions:

High-resolution-x-ray-diffraction (HRXRD) was performed on the MRD PRO Thin Film Diffractometer instrument to determine the crystallographic structure and to validate the atomic ratio of In:Al. The <002> peak was analyzed; using Bragg's law, known lattice constants of $In_xAl_{1-x}N$ materials, and the spacing between peaks, the In:Al ratio were calculated in all samples to be $0.15 < x < 0.20$, near-desired $x \sim 0.18$.

Atomic force microscopy (AFM), performed using the Asylum MFP3D instrument, was used to characterize surface topography and roughness, which is defined to be the root-mean-square (RMS) height of a scanned region of the sample. An inversely proportional relationship between roughness and InAlN thickness would be expected, which was not observed in Series-2. For this series, the 10.0 nm InAlN-layer thickness had a RMS roughness of 1.82 nm, much lower than the other two samples grown.

Electrical results (see Figure 3 and 4), done using the Hall patterns from photolithography, were measured using the Lake Shore Hall measurement system; parameters investigated include mobility, carrier density, and sheet resistance.

The average hall mobility of the 2.5 nm GTID sample of Series-1 was a factor five higher than the other two samples, at a value of 488 cm^2/Vs. Additionally, its carrier density was the highest at a value of $1.13 * 10^{13}$ cm^{-2}, and it had the lowest sheet resistance of 1570 $\Omega/\square$. When the Series-2 samples were grown to optimize InAlN-layer thickness, the 10.0 nm InAlN-layer thick sample had the highest mobility, carrier density, and lowest sheet resistance.

At a deeper GTID, the portion of the GaN layer grown at the lower temperature would be much rougher, causing the 2DEG and the InAlN-layers to also be rough and the material quality would be poor. A GTID at the interface will add a high unintentional dopant concentration near the 2DEG, scattering carriers. These arguments could explain why optimum electronic properties were observed at the 2.5 nm GTID. For the InAlN-layer thickness, a thinner layer will cause a loss of charge in the 2DEG from the Schottky barrier height but a thicker layer will decrease transconductance for HEMT devices.

Despite the observations of this work, there are several further steps to be made on the project before the material can be commercialized. The first includes confirming these reported trends to confirm the optimization of these growth parameters. Beyond this, there are other growth conditions that can be worked on, such as growing the precise stoichiometric $In_{0.18}Al_{0.82}N$.

Acknowledgments:

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References:

[1] Mishra, U. K., Parikh, P., and Wu, Y. F AlGaN/GaN HEMTs; an overview of device operation and applications. Proceedings of the IEEE, 90(6), 1022-1031 (2002).

[2] Hoi Wong, M., Wu, F., Hurni, C. A., Choi, S., Speck, J. S., and Mishra, U. K. Molecular beam epitaxy of InAlN lattice-matched to GaN with homogeneous composition using ammonia as nitrogen source. Applied Physics Letters, 100(7), 072107-072107 (2012).

[3] Jeganathan, K., Shimizu, M., Okumura, H., Yano, Y., and Akutsu, N. Lattice-matched InAlN/GaN two-dimensional electron gas with high mobility and sheet carrier density by plasma-assisted molecular beam epitaxy. Journal of crystal growth, 304(2), 342-345 (2007).