# PVD of AlN Nucleation Layers for GaN-based LED Structures: A Cheaper and Brighter Alternative

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**Keywords: AlN, PVD, GaN, LED, MOCVD**

## Abstract

**A physical vapor deposition (PVD) process for AlN nucleation layers has been developed to improve the manufacturing and performance of GaN-based light emitting diodes. AlN nucleation layers were prepared and their properties were analyzed via X-ray diffraction, AFM, and with a thin film analyzer. The AlN layers exhibited a highly oriented crystalline structure with smooth surfaces and good thickness uniformity. LEDs grown via MOCVD on sapphire using the AlN nucleation layers were shown to simplify the MOCVD growth process and improved the performance of LEDs when compared to devices grown on sapphire using a conventional growth approach.**

## INTRODUCTION

The successful implementation of solid state lighting (SSL) promises to impact innumerable products, systems and sectors around the world, in a wide range of industrial, commercial and residential applications. In addition to improved functionality, the possibility of replacing inefficient, short-lived incandescent light sources with SSL can reduce energy consumption for lighting, decrease operational and support costs, and provide lighter, more compact lighting with new form factors. SSL sources can also replace fluorescent and high pressure sodium light sources, eliminating sources of mercury and other toxic material and reducing energy consumption, while improving lighting quality. In the US, lighting makes up more than 20% of the total national energy consumption [1] and this presents an opportunity for appreciable energy savings with SSL.

Cost reduction in GaN-based LEDs is a continuous requirement and goal for LED manufacturers in order to enable cost-effective production of SSL. Simplification of the growth of the LED structure is one approach that can contribute to the reduction of the cost of SSL. The standard MOCVD process for LEDs grown on sapphire involves a two-step nucleation process that starts with a low temperature thin GaN deposition, followed by a high temperature growth to complete the GaN buffer. The N+ layer of the LED is then grown on this nucleation layer. Additionally, growth of the nucleation layer is frequently preceded by a high temperature anneal of the sapphire. Temperature cycling the MOCVD tool takes a significant amount of time where the system is not utilized for growth. The use of a PVD nucleation layer eliminates the need for low temperature nucleation and enables direct growth at high temperature. Figure 1 (a) shows a baseline LED structure grown on sapphire using a standard two-step buffer layer. As shown in Figure 1 (b), the use of a PVD nucleation layer simplifies the MOCVD epitaxial process for InGaN-based devices by eliminating growth steps, enabling lower cost through a shorter overall process. In this paper, results from the development of AlN nucleation layers grown via PVD are discussed and compared with typical nucleation layer technologies with regards to LED manufacturability and performance.

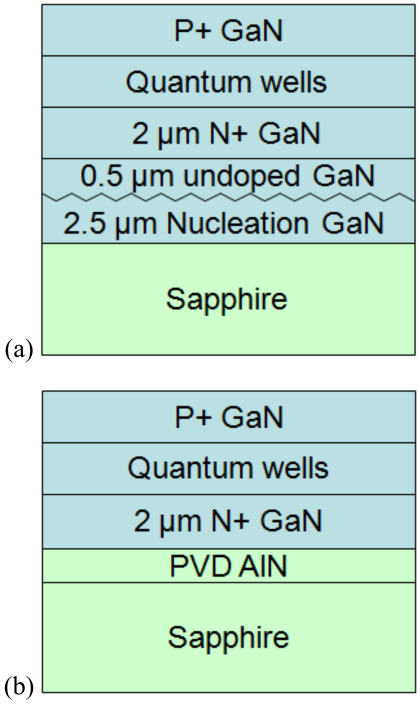

Figure 1: (a) Standard MOCVD LED structure on sapphire using 2-step nucleation process; (b) LED on sapphire using PVD nucleation layer.

## EXPERIMENTAL

Using a custom processing tool developed at Kyma Technologies, a PVD process for AlN nucleation layers on substrates up to 4” diameter was developed to provide excellent materials properties, layer thickness uniformity, and repeatability in a cost-effective approach. For this study, 2 inch diameter sapphire substrates were used and deposition processes for AlN layers from 25nm to 1µm in thickness were developed. The sapphire substrates were run in a 3 x 2 inch configuration in the PVD system. Following deposition the layers were characterized using a Panalytical X’Pert X-ray diffractometer (XRD), a Digital Instruments atomic force microscope (AFM), a Filmetrics F20 Thin Film Analyzer, and optical microscopy. GaN epilayers and LED structures were grown on the nucleation layers using an Aixtron MOCVD growth system. LEDs were fabricated and the electroluminescence performance of the devices was measured and compared to devices fabricated using the standard MOCVD growth approach. LED power output was measured using an integrating sphere after the chip was packaged.

## AlN CHARACTERIZATION

X-ray characterization of the (0002) rocking curve was performed on 350nm thick AlN nucleation layers. The rocking curve exhibited a sharp, narrow peak (~25 arcsec) with high intensity with a broad background peak with low intensity as much as one order of magnitude below the main peak. The lineshape of the rocking curve indicates a highly oriented columnar crystalline structure in the film, which is a result of optimizing the depositions conditions of the layer.

Figure 2 shows an AFM image of the surface of a 350nm thick AlN nucleation layer. The layer is comprised of a high density of islands/columns with a RMS roughness of 7.8Å. This provides a highly uniform nucleation surface for the growth of GaN epilayers. The size of the islands increases with increasing film thickness. For thinner film thicknesses (25nm), the RMS roughness was very similar, although the island morphology was much less pronounced.

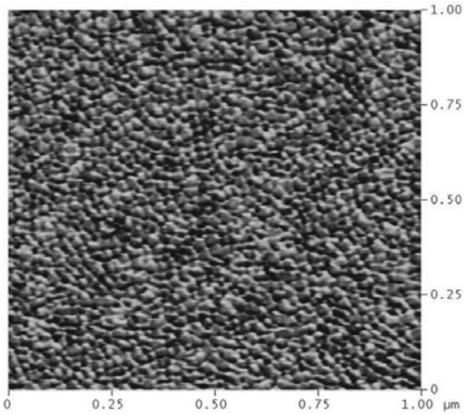

Figure 2: AFM image of a 0.35µm thick AlN nucleation layer. The RMS roughness of the film is 7.8Å.

Thickness uniformity of the AlN layers was measured using a Filmetrics F20 Thin Film Analyzer. Samples with 25nm and 350nm thicknesses were analyzed. The thickness uniformity variation was calculated using a measurement at the center of the wafer and an average of four measurements at the edge of the substrate. On-wafer uniformity was very good for both the 25nm and 350nm AlN layers and is shown in Table 1. Wafer-to-wafer uniformity within the 3x2 wafer batch was good with an average film thickness variation of 2.5% for 350nm thick films. Batch-to-batch uniformity had an average film thickness variation of 3.4%.

| AlN film thickness | Average Uniformity Variation | Maximum Uniformity Variation | Minimum Uniformity Variation |
|---|---|---|---|
| 25nm | 1.0% | 2.8% | 0.4% |
| 350nm | 0.9% | 1.7% | 0.1% |

Table 1: Filmetrics AlN layer uniformity measurements.

## GaN GROWTH AND LED PERFORMANCE

Using optical microscopy, the GaN epilayers using the standard nucleation approach and the AlN nucleation layers were both featureless at 200x magnification. Figure 3 shows an AFM image of a GaN layer grown on an AlN nucleation layers. The AFM analysis showed the layers grown on the AlN layers had a similar morphology to that typically reported for growth on sapphire with a low temperature buffer layer, showing the interchangeability of the AlN nucleation layer with the standard MOCVD process.

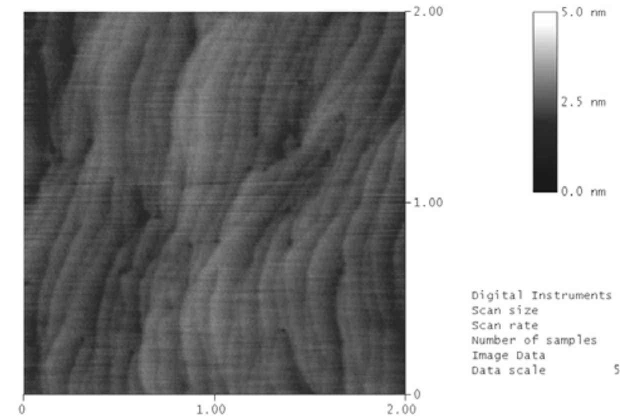

Figure 3: AFM image of an MOCVD GaN epilayer grown on an AlN nucleation layer. The morphology is similar to that typically reported for growth on sapphire with a low temperature buffer layer.

LED device structures were grown on the 25nm AlN nucleation layers. The growth process used direct high temperature growth on the AlN, simplifying the growth process as shown in Figure 1.

A comparison of LED performance parameters of devices grown on MOCVD nucleation layers and those grown on PVD AlN are presented in Table 2. At 20mA injection current, the forward voltage and the wavelength for both LEDs are comparable, while the output power for AlN PVD- based structures is 12.6% higher. Preliminary results from growth experiments show that AlN PVD and standard MOCVD nucleation layers have comparable yields for the LED epiwafers and devices.

| LED Property | Standard LED Process | LED with AlN Nucleation |
|---|---|---|
| Forward Voltage, 20mA (Vf) | 3.37 | 3.40 |
| Output Power (mW) | 23.8 | 26.8 |
| Wave-length (nm) | 448.8 | 451.9 |

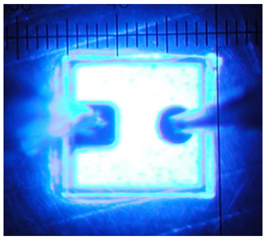

Table 2: LED performance for devices grown on sapphire using the standard MOCVD process and the AlN nucleation layer. The figure on the right shows the topology of the LED die.

## CONCLUSIONS

Aluminum nitride nucleation layers deposited by PVD have been shown to exhibit highly oriented crystalline structure with smooth surfaces and good thickness uniformity. Growth of LED structures on the AlN layers

When compared to a conventional manufacturing approach using MOCVD nucleation and base layers for the LED structure, PVD AlN offers a cost reduction potential through simplification of the MOCVD growth process, reducing growth time in the process system and increasing the production throughput of existing growth systems.

## ACKNOWLEDGEMENTS

The authors would like to Dr. R. Fu at Tekcore for the MOCVD growth and the LED fabrication and testing.

## REFERENCES

[1] http://www.eia.doe.gov/

## ACRONYMS

AFM: Atomic Force Microscopy
LED: Light Emitting Diode
MOCVD: Metalorganic Chemical Vapor Deposition
PVD: Physical Vapor Deposition
SSL: Solid State Lighting
XRD: X-ray diffraction, X-ray diffractometer