# Epitaxial Deposition of Low-Defect AlN and AlGaN Films

by

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# ABSTRACT

The field of group III-nitrides semiconductors has seen remarkable developments during the last two decades. They are recognized as the most promising materials for a wide field of optoelectronics and electronic devices. AlN and AlGaN are the semiconductor materials of preference for optoelectronic devices in the ultraviolet (UV) wavelength range and for high power, high frequency electronic devices. Significant advances have been made in the production technology of UV light emitting diodes (UV-LEDs) and high electron mobility transistors (HEMTs) during the last decade. However, significant efforts are needed to develop next generation of devices.

One of the key issues hindering the progress of these devices is the presence of high density of dislocations in AlN epitaxial layers. III-nitride epitaxial layers are grown on foreign substrates due to the limited availability of native nitride substrates. Heteroepitaxial growth of AlN and AlGaN over sapphire, which is the typical substrate of choice, results in large densities of misfit dislocations, usually in the vicinity of $10^{10}$ $cm^{-2}$ due to substantial lattice mismatch. Subsequent formation of threading dislocations tends to degrade the device properties. These defects are responsible for enhanced nonradiative recombination thereby lowering the efficiency of UV LEDs. Moreover, nitride films grown over sapphire beyond critical thicknesses suffer from cracking due to the strong tensile strain and difference in thermal expansion coefficients between substrate and epilayers. While native AlN substrates can alleviate this issue, presently commercially available AlN substrates are cost-prohibitive, have usable area limitations and suffer from excessive absorption. The necessity for a high-quality native substrate or template for nitride-based device development is apparent.

Objective of my research was to develop low-defect AlN and AlGaN templates to enable pseudo-homoepitaxial deposition of UV-LEDs. Two approaches have been used to achieve this objective. Firstly, hydride vapor phase epitaxy (HVPE) process was used to prepare thick AlN films with lower defect density. Interactions of dislocations in thicker films result in their annihilation. Secondly, since thick films grown on sapphire tend to crack beyond a critical thickness (3-5 μm), epitaxial lateral overgrowth (ELOG) approach was employed to eliminate cracking and to further reduce the defect density.

The growth technique was switched from HVPE to Metalorganic chemical vapor deposition (MOCVD) due to much improved material quality with the later method.

An HVPE growth system was first designed and constructed from ground up [1]. It is a vertical system with a quartz chamber and a resistively heated furnace. $AlCl_3$ and $NH_3$ were used as the precursors. $AlCl_3$ was generated by passing HCl gas (diluted with $H_2$) through Al metal source. A linear relationship between growth rate and HCl flow rate indicated that the growth rate is limited by mass transportation. Growth parameters including temperature, chamber pressure and V/III ratio were optimized to improve the film quality. Thick films of AlN with thicknesses exceeding 25 μm were grown with growth rates as high as 20 μm/hr [2]. These films were extensively characterized by scanning electron microscopy, atomic force microscopy, high-resolution x-ray diffractometry (HRXRD), and photoluminescence (PL). AFM study revealed that surface roughness of HVPE grown AlN films strongly depends on the growth rate. The lowest RMS roughness for HVPE grown film was 1.9 nm. These films had typical (002) full-width at half maximum (FWHM) values ranging from 24 – 400 arcsec, depending on the growth rate of the respective films. The crystalline quality of the films was also found to be deteriorating as the growth rate increased. It is inferred that the growth mode changes from two dimensional to three dimensional at higher growth rates due to reduced adatom migration length. PL spectrum exhibited near-band-edge (NBE) emission line along with broader deep level-related bands, presumably due to donor-acceptor and band-acceptor transitions. Etch-pit density measurement revealed threading dislocation density of $1x10^9$ $cm^{-2}$, which is at least 5 times smaller than conventionally grown MOCVD films. Homoepitaxial deposition of GaN films and AlGaN/GaN HEMT structure was carried out by MOCVD using HVPE grown AlN layers as templates. Improved properties of the GaN film and enhanced performance of HEMT are ascribed to reduced dislocation density of AlN templates.

AlN and AlGaN films grown on sapphire substrate tend to crack and even peel off beyond a critical thickness of 2 -5 μm. To prevent thick films from cracking, ELOG technique was utilized. This technique has been successfully employed to deposit several hundred micrometers thick crack-free GaN films, which demonstrate 2-3 orders of magnitude reduction in TDD. Crack-free thick layers of AlN and AlGaN were deposited using ELOG technique. MOCVD was used as the growth method due to improved material quality. Trimethylaluminum (TMAl), trimethylgallium (TMGa) and ammonia (NH3) were used as the precursors. The growth was performed under low pressure with $H_2$ as the carrier gas. First about 2 μm thick AlGaN layers were deposited on c-plane sapphire substrates. Such thin AlGaN layers, grown without any dislocation reduction technique, usually show TDD in the mid $10^{10}$ $cm^{-2}$ range. Linear trench patterns along $[1\bar{1}00]_{AlGaN}$ were fabricated in the AlGaN layers using conventional photolithography and RIE (reactive ion etching). The patterns included 2 μm wide mesas with 5 μm wide trenches. The trenched templates were reloaded into the MOCVD chamber for overgrowth of AlN and high Al-content AlGaN. The overgrowth was carried out at a temperature of 1200 $^{o}$C with the growth rate of 1 to 2 μm/hr. Migration enhanced MOCVD (MEMOCVD®) [3] was combined with ELOG approach to develop a novel Migration Enhanced Lateral Epitaxial Overgrowth (MELEO) technique [4]. As part of this novel technique, precursor pulses were varied to control the ratio of lateral/vertical growth rate. Coalescence related low-angle grain boundaries and edge dislocations were reduced by promoting coherent coalescence using MELEO technique. Fully coalesced, AlN and AlGaN films with thicknesses as high as 30 μm were deposited. SEM was used to characterize the geometry of the coalescence region. HRXRD was used to evaluate the crystalline quality of the thick films X-ray rocking curves for AlN $(0002)$ and $(10\bar{1}2)$ diffractions had full-width at half maximum (FWHM) values of 150 and 291 arcsec, respectively. AFM images illustrate much improved surface morphology with long parallel atomic steps. TEM study shows bending and interaction of dislocations. Threading dislocation density was reduced by up to two orders of magnitude to 4.34 x $10^{8}$ $cm^{-2}$. The material grown has been used for pseudo-homoepitaxy of UV-LEDs, SAW based devices, HEMTs, and RF switches [5-9]. UV LEDs with 310 nm emission wavelength on a low-defect AlN template exhibited much improved performance with 3X increase in optical power and 6X increase in the device lifetime. This performance improvement is attributed to the low-defect nature of the AlN template.

In summary, HVPE process was established to deposit thick AlN films at faster growth rates; a novel MELEO technique was developed to reduce dislocation density in

AlN and AlGaN films by two orders of magnitude. Pseudo-homoepitaxy of UV LEDs over such low-defect templates lead to significant improvement in device performances.