Characterization of AlGaN Material Quality for use in Deep-Ultraviolet Light Emitting Diodes

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Abstract:

High-power deep-UV light emitting diodes and laser diodes can be used in a variety of applications, including the detection of anthrax and other biological agents, water purification, and high-density optical storage. Deep-UV LEDs are composed of an AlN template layer and AlGaN active device layers grown epitaxially by metal-organic chemical vapor deposition on c-plane sapphire. To achieve efficient LEDs with reasonable lifetimes and light output, the material must be high quality. The project focuses on characterizing the crystal quality and surface morphology of the AlN and AlGaN using X-ray diffraction, atomic force microscopy, and other methods, and relating these qualities to device performance. Additionally, we seek to determine the relationship between AlN layer quality and AlGaN layer quality. Plan-view transmission electron microscopy data suggest that current dislocation densities in the AlN template layers range from 5×10^9 cm^{-2} to greater than 1×10^{10} cm^{-2}, which will propagate into subsequent layers and affect device performance.

Finally, we are designing a procedure using x-ray rocking curve analysis to determine the dislocation density in the AlGaN layers as a function of growth parameters, including growth temperature, pressure, and composition, as well as AlN template quality.

Introduction:

Compared to other light sources, optimized LEDs use little power, are extremely compact, generate little heat, are inexpensive, and offer very long lifetimes. Deep-UV LEDs and LDs have the potential to detect and decontaminate biological agents including anthrax, purify water, allow for non-line-of-sight communications, dramatically increase the storage capacity of optical storage, and provide efficient sources of white light. Current technology allows for near-UV LEDs to the mid-300 nm range. The target wavelength is 280 nm. To achieve the listed advances, however, the LEDs and LDs must be of sufficiently high quality.

Procedure:

The thin films were grown epitaxially on two-inch diameter (001) sapphire by metalorganic chemical vapor deposition (MOCVD). The wafer was heated to ~1000°C. Trimethylaluminum and trimethylgallium were injected in nitrogen or hydrogen carrier gas with gaseous ammonia into the MOCVD reactor. The precursors decomposed in the hot zone to deposit on the sapphire wafer, forming single-crystal AlN, AlGaN, or GaN layers.

We used several different characterization techniques to determine the quality of the layers. The two most common techniques were optical microscopy and x-ray diffraction (XRD). Optical microscopy gives qualitative data about the surface of the material. XRD gives quantitative data about the crystal structure quality, in particular the density of edge and screw dislocations. We took rocking curve (w-scans) XRD data of the (002) plane and (201) plane to find the density of screw- and edge-type dislocations, respectively [1].

Ideal films would be transparent, free of surface defects, and exhibit narrow XRD rocking curve peak widths.

Since the AlN layer is merely a template layer for the actual AlGaN device layers, we wanted to

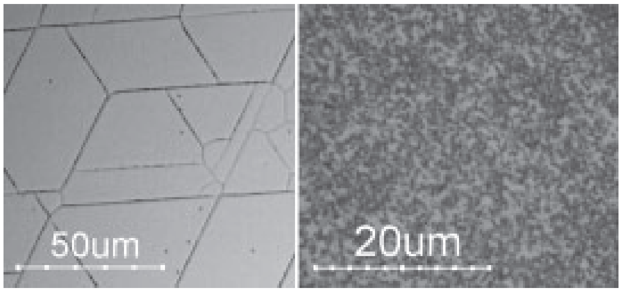

Figure 1, left: Optical image of cracking on surface of AlN template. Figure 2, right: Optical image of impurity deposits on AlGaN (dark spots).

determine a method for taking quantitative measurements of AlGaN layer quality relative to the AlN template layer. The on-axis (002) measurement is trivial to take, since the AlN and AlGaN peaks are separated by a few degrees. The off-axis peaks, however, proved to be much more difficult, since the correct angles were not known. By comparing the relative positions of the (002) peaks of AlN and AlGaN, we could determine the relative composition. Using this data, we could then determine the correct diffraction angles for any specified plane by interpolating between AlN and AlGaN parameters. We attempted scans of the (102), (201), and (204) directions. Non-reproducibility issues related to AlN template growths precluded experiments to investigate AlGaN device layers.

We explored several sets of conditions to improve reproducibility. Temperature and pressure were changed routinely. Additional modifications were made to the reactor design to eliminate pre-reactions between the gases.

Results and Analysis:

Optical microscopy showed material with a variety of defects, including cracking (Figure 1) and impurity deposits (Figure 2). High-quality material should be homogeneous and optically smooth.

(002) rocking curves of AlN templates yielded significant differences in material quality, as illustrated in Figure 3. The FWHM increased an order of magnitude between samples. To a rough approximation, the threading dislocation density is proportional to the square of the XRD rocking curve FWHM, indicating a significant degradation in material quality. The cause of this increase is still unknown.

The attempt to characterize the AlGaN quality indicated that the quality must improve before we can take quantitative data. The AlN and AlGaN peaks were so broad and close together in the (102), (201), and (204) scans that we were not able to reliably separate them (see Figure 4). If the material quality improves, the peaks should narrow, allowing the two peaks to be distinguishable and allowing for quantitative analysis on each.

Future Work:

Prior deposits on reactor quartzware may affect subsequent material growth. To investigate the source of this variability, the quartzware will go through a high-temperature HCl bake to remove deposits from the surface. Clean quartzware will be tested against dirty quartzware for any affects on material quality, and to determine the length of time for stable growth. Early tests indicate there is similar variation in the (201) XRD FWHM.

Acknowledgments:

John Kaeding and Dr. Nakamura have provided excellent support and instruction throughout this project. As the old adage goes, one can learn more in failure than in success. I find that particularly true here, for I have learned not only the difficulties of semiconductor fabrication, but also of the very process of scientific research. This work was completed with support from DARPA and NSF.

References:

[1] B. Heying, X. Wu, S. Keller, Y. Li, D. Kapolnek, B. Keller, S. DenBaars, J. Speck. Appl. Phys. Lett. 68 (5), 29 Jan 1996. 643-545.

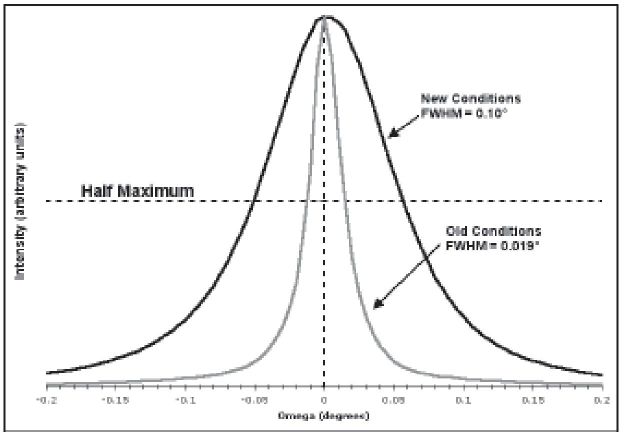

Figure 3, above: (002) XRD data of AlN Templates. Narrow peaks indicate better material quality.

Figure 4, below: (102) XRD data of AlN/AlGaN layers. This peak is likely actually composed of two peaks.