Cantilever Epitaxy of GaN Receives R&D100 Award

by ***D. M. Follstaedt, C. C. Mitchell, A. A. Allerman, D. D. Koleske, K. H. A. Bogart, A. J. Fischer, N. A. Missert, C. I. H. Ashby, P. P. Provencio, J. J. Figiel, K. W. Fullmer, K. C. Cross, M. P. Moran, A. K. Norman, G. M. Peake, L. Griego, A. Ongstad, and J. Sergeant***

Motivation—The semiconductor GaN has a large bandgap that allows optical emission in the visible and UV ranges by using its alloys with In and Al. Although GaN wafers are not available for device processing (like widely used Si wafers), GaN can be grown on sapphire and SiC wafers. However, the atomic spacing of GaN does not match these substrates, causing high densities of dislocation defects in the GaN that directly reduce optical emission. It is therefore important to reduce dislocation density to enable efficient light emission. Optical emission from GaN is thought to have the potential to provide general illumination with 50% efficiency, which could reduce U.S. electricity use by up to 10%.

Accomplishment—Our development of cantilever epitaxy (CE) to grow GaN with low dislocation density is described in previous *Physical and Chemical Sciences Center Research Briefs* (2001, p. 74; 2002, p. 18; and 2003, p. 20). This method minimizes the contact area of GaN on sapphire that produces these defects by nucleating the GaN on narrow mesas and growing it laterally over trenches as in Fig. 1. Adjacent cantilevers are grown together to coalesce into a uniform solid. After basic advantages of CE were identi-fied, we showed that remaining dislocations could be further reduced by turning them from vertical to horizontal and by identifying growth methods producing inherently fewer defects. However, we also found new non-radiative centers called "dark-block defects". These defects were caused by tilted cantilevers that did not coalesce properly, leaving cracks with additional dislocations around them. The defects were eliminated by increasing the nucleation density, by increasing the trench depth, and by controlling the facets on cantilever faces.

To determine the density of remaining dislocations accurately, we developed special imaging techniques for transmission electron microscopy to assure that all dislocations were detected. When used with scanning cathodo-luminescence and atomic-force microscopy images, our final dislocation density can be confidently stated as $2\text{-}5\times10^{7}/\text{cm}^{2}$. This is an order of magnitude or more below that for conventional planar growth of GaN on sapphire. The low density improves the output of light-emitting diodes (LEDs). Fig. 2 shows maps of the photo-luminescence output from identical InGaN quantum wells grown on two half wafers of GaN, one grown by CE and the other by conventional planar growth. The greater intensity from the CE GaN wafer directly demonstrates that dislocations reduce light emission and that cantilever epitaxy can increase the light output of LEDs.

Significance—The importance of CE GaN is demonstrated by our receiving a 2004 R&D 100 award for its development. Winning this award required not only technical achievement, but demonstration of commercial viability as well. Cantilever epitaxy has the advantage that once the trenches are patterned into the wafer, the GaN layer and LED structure can be formed with only one metallorganic chemical vapor deposition (MOCVD) growth. Competing schemes for reducing dislocations require multiple growths or very thick growth; both are more expensive and have other disadvantages. Thus CE GaN could enable economically the widespread use of solid-state lighting needed to achieve significant energy savings. Low-defect GaN appears potentially important for high-frequency electronic devices also.

Sponsors for various phases of this work include: DOE Office of Basic Energy Sciences, DOE Office of Energy Efficiency & Renewable Energy, Laboratory Directed Research & Development, and Nuclear Weapons/Science & Technology

Contact: David M. Follstaedt; Radiation-Solid Interactions, Dept. 1111
Phone: (505) 844-2102, Fax: (505) 844-7775, E-mail: dmfolls@sandia.gov

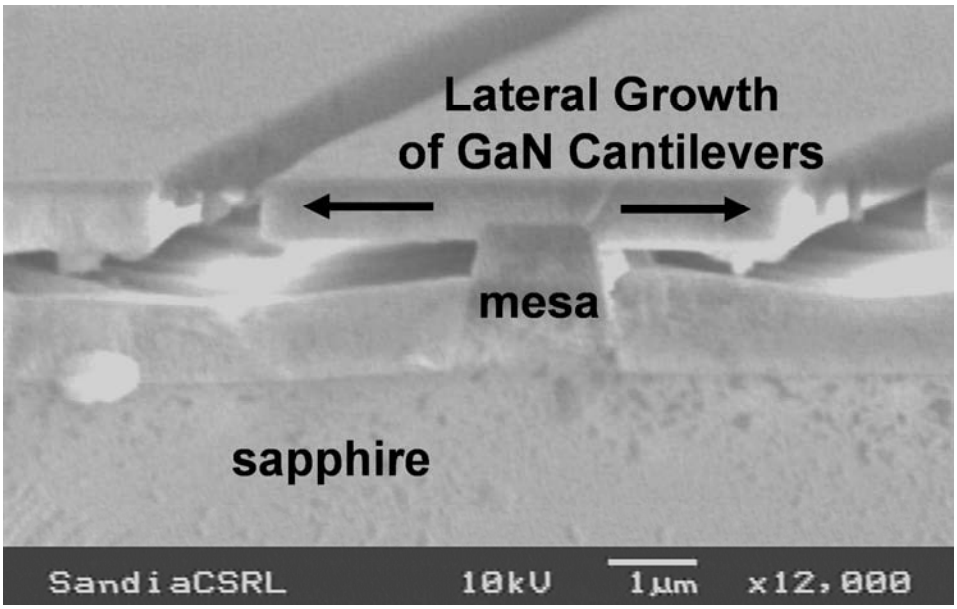

Figure 1. Cross-section scanning electron micrograph showing GaN growing off sapphire mesas and over trenches toward adjacent GaN cantilevers. Some GaN also grows in trenches between mesas.

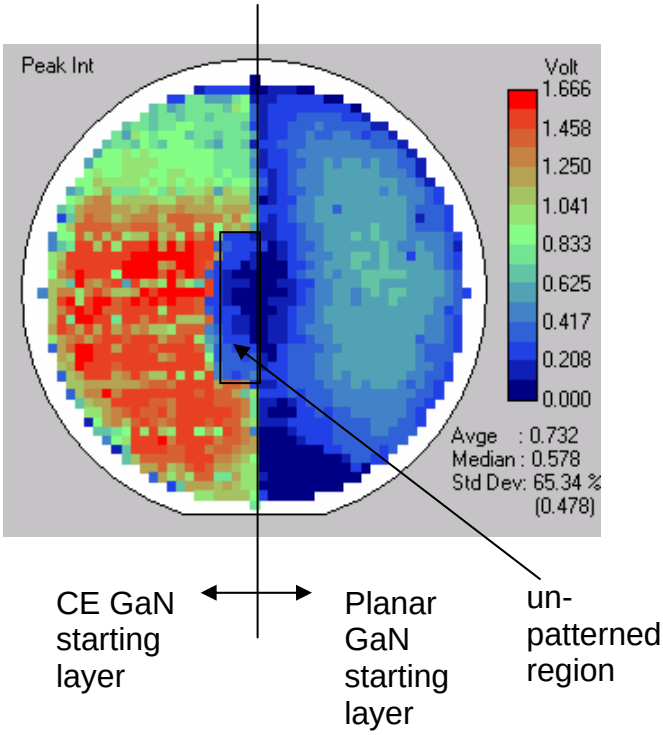

Figure 2. Photoluminescence map showing the intensity of emitted light from CE GaN (left) and conventionally grown planar GaN (right) when irradiated with a 325 nm HeCd laser. Both half-wafers were identically processed to form optically emitting InGaN quantum wells for LEDs. The light emission from CE GaN is 2 to 3 times brighter. (Data courtesy of Lumileds Lighting).