Cantilever Epitaxy: Multi-Step Optimization of Growth and Substrate Processing

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Motivation—For GaN grown on any readily available substrate the large lattice mismatch between GaN and the substrate results in 10^8 — 10^{10} threading dislocations per cm^2. For light emitting devices, these dislocations act as non-radiative centers and ultimately limit device performance. To reduce the GaN dislocation density on lattice mismatched substrates, a unique growth technique, called cantilever epitaxy (CE) has been developed and improved upon at Sandia. This is particularly important for the fabrication of vertical cavity surface emitting lasers (VCSELs) and light emitting diodes (LEDs) below 400 nm.

Accomplishment—Our prior research on CE focused on establishing growth conditions to turn dislocations that originate from the growth zone on top of the post. Once turned these dislocations no longer interfere with device layers that are grown on top. The dislocation turning was accomplished by choosing growth conditions that form a pyramidal gable bounded by $(11\bar{2}2)$ facets on top of the post. After forming the pyramidal gable, the lateral growth rate is increased, causing the dislocations to turn and run parallel to the growth plane. Using this method for dislocation turning, the dislocation density was reduced for GaN CE films by 2-3 orders of magnitude.

Cathodoluminescence (CL) images showed an additional array of dislocations formed during coalescence of the cantilever wings, referred to as dark-block defects. The dark-block regions are observed as discontinuities in optical microscopy and scanning electron microscopy (SEM). Transmission electron microscopy (TEM) showed that the discontinuities are cracks where two misoriented cantilevers joined. Figure 1 shows a scanning CL and SEM image of these defects.

To eliminate the dark-block defects three aspects of CE growth were closely investigated. These steps included the nucleation layer (NL) and gable growth, the lateral growth over the trench, and the morphology of the cantilevers prior to coalescence. The density of the NL affects the quality of the gable, illustrated in Fig. 2. A uniform gable is formed when the NL is dense and uniform. The differences between these two gables can be monitored using optical reflectance. Once the gable is formed, the growth conditions are changed to enhance the lateral overgrowth. The cantilevers must grow laterally and span the trench before the trench fills in. Improvements in the sapphire etching and mask uniformity have aided in the fabrication of sapphire cantilever substrates with deeper trenches, allowing for more latitude in the growth conditions. Prior to coalescence the growth conditions $(11\bar{2}2)$ are again changed to form facets. These facets are then allowed to coalesce and the cantilevers meet smoothly. When these growth criteria are successfully accomplished, GaN CE wafers can be grown with dislocation densities of 5×10^7 cm^{-2} as shown by CL in Fig. 3.

Significance—Careful optimization of the CE process has led to the elimination of the detrimental dark block defects while producing films with fewer threading dislocations. The fundamental study of how and why GaN crystals coalesce, whether for CE or for planar films, yields valuable information that will lead to the optimization of GaN heteroepitaxy. These films are currently being tested for UV LEDs; preliminary results indicate a significant improvement for wavelengths < 380 nm.

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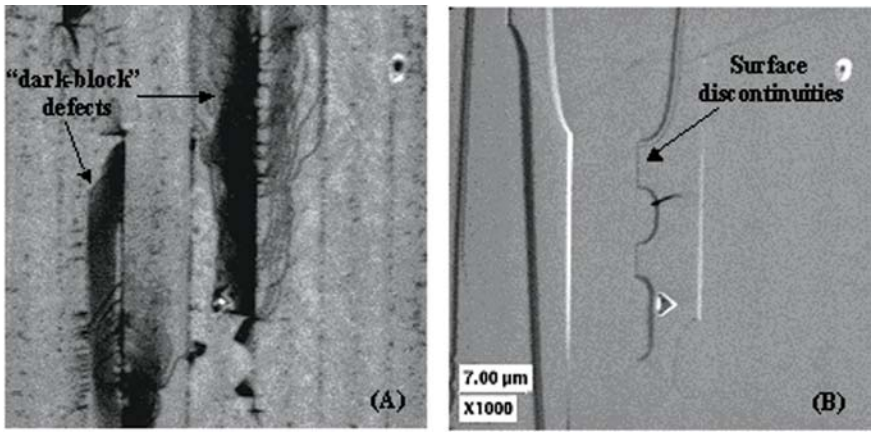

Figure 1. (A) Scanning panchromatic CL and (B) secondary electron (SE) micrographs of a coalesced cantilever substrate where surface discontinuities are present. The surface discontinuities seen in the SE images directly correlate with the "dark-block" defects seen in the cathodoluminescence scan.

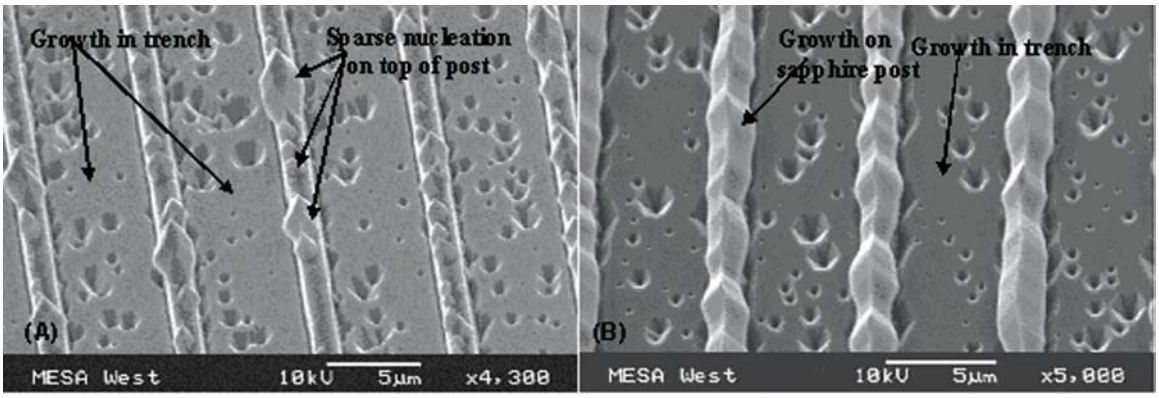

Figure 2. SEM images of (A) a nucleation layer condition that resulted in non-uniform gable formation and (B) a nucleation layer condition where the subsequent gable growth is uniform along the length of the post.

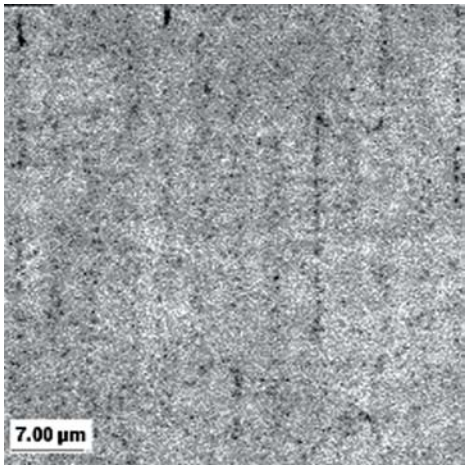

Figure 2. Scanning cathodoluminescence scan of coalesced cantilever epitaxy film without dark-block defects. Overall dislocation density is 5 x 10^7 dislocations/cm^2.