Cantilever Epitaxy: A Simple Lateral Growth Technique for Reducing Dislocation Densities in GaN and Other Nitrides

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The high threading dislocation (TD) densities found in GaN that has been grown directly on flat substrates degrade both the electronic and photonic properties of the material. The new technique of cantilever epitaxy (CE) can reduce the density of dislocations by 2 or more orders of magnitude. CE employs prepatterned substrates to provide reduced-dimension mesa regions and etched trenches that are spanned by lateral growth of GaN or AlGaN. The substrate is prepatterned with narrow lines and etched to a depth that permits coalescence of laterally growing III-N nucleated on the mesa surface before vertical growth fills the etched trench. Low dislocation densities typical of epitaxial lateral overgrowth (ELO) are obtained in the cantilever regions and the TD density is also reduced over the mesas up to 1 micrometer from the edge of the mesa support regions.

A major obstacle on the path to GaN-based microelectronic integrated circuits and long-lived, high performance optoelectronic devices and circuits has been the inherently high densities ($10^8-10^{10}$/cm$^2$) of threading dislocations (TDs) in epitaxially grown GaN [1]. Although these TD densities have not prevented the development of high-brightness light-emitting diodes (LED), they produce unacceptably high reverse-bias leakage currents in p-n junction devices such as high-electron-mobility transistors (HEMTs) and field-effect transistors (FETs) [1]. They also shorten the lifetime of III-N laser diodes. The solution of these problems will require a GaN substrate with TD densities less than $10^5$/cm$^2$.

Achieving such low TD densities has been an elusive goal due to the lack of a good substrate that matches the lattice constant and thermal expansion properties of GaN. The ideal substrate would be low-TD-density, single-crystal GaN wafers of at least 2" diameter. Since such material is not readily available, epitaxial GaN and related III-N materials are generally grown on planar wafers of wurtzite or cubic materials with up to 16% lattice mismatch with GaN. The most common substrate is sapphire, Al$_2$O$_3$ (0001), which is available as high-quality wafers at reasonable cost. However, GaN growth directly on planar Al$_2$O$_3$ produces $10^8-10^{10}$ TDs/cm$^2$.

Several approaches have achieved considerable success in reducing TD densities, but previously reported techniques are very time-consuming to implement. These techniques reduce dislocation densities to the $10^7$/cm$^2$ range in selected regions of a wafer. These include epitaxial lateral overgrowth (ELO or LEO) [2,3], pendeoepitaxy (PE) [4].
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and lateral overgrowth from trenches (LOFT) [5]. While each technique produces
selective areas on a wafer that possess the low TD densities (<10'/cm²) required for
electronic and long-lived laser devices, they are complex, multistep processes requiring
dielectric masks and regrowth. In each case, broad-area GaN is first grown on a (0001)
sapphire, (0001) 6H-SiC, or Si(111) substrate; this initial GaN layer displays the typical
10⁴-10⁶/cm² TD density characteristic of standard GaN epitaxial layers and serves as the
seed region for subsequent GaN regrowth. GaN grown directly over the seed region
retains the initial high TD density while regions of lateral growth over the dielectric mask
in ELO or from etched GaN walls in PE and LOFT display reduced TD densities. High
concentrations of TDs are generally observed at the mask edges and both TDs and voids
are common at the coalescence front over the dielectric mask.

Cantilever epitaxy (CE) is a simplified approach to growing low-TD GaN and
other III-N materials that requires a single substrate etch to form μm-scale support mesas
in sapphire or other substrate materials prior to a single, temperature-varied nitride
growth sequence. The process begins with growth of a standard low-temperature
nucleation layer on the previously patterned substrate. This is followed by a limited
growth of GaN (≥0.4 μm) at high temperature to produce a coalesced, smooth surface and
GaN sidewalls from which to initiate rapid lateral growth. The temperature is then
increased to produce more rapid lateral growth than vertical growth. Cantilevers grow
laterally from the side surfaces of the GaN that grew during the first high-temperature
phase. To achieve a continuous GaN surface, the cantilevers are grown to coalescence.

This process results in cantilevers with very few TDs (10'/cm²). Appreciable
suppression of TD formation above the support mesa also occurs over a distance up to 1
μm in from the mesa edge, as determined by cross-section transmission electron
microscopy (TEM), atomic force microscopy (AFM), and cathodoluminescence (CL).
The coalescence fronts exhibit extended regions with no TDs detectable by AFM and CL.

For the samples presented here, a BCl₃-based plasma in an inductively-coupled
plasma reactor was employed etch approximately 2-μm-deep trenches into sapphire
wafers. The mask was one developed for mechanistic studies of standard ELO [6] and
consisted of a series of parallel lines with different mesa and trench spacings. The results
presented here are from growths with regions masked for 4-μm supports and 8-μm
trenches. The strong ionic component of the plasma etch produced 2.8-μm mesas with 8-9
μm trenches. Two crystallographic orientations were included in the mask, with one set
forming lines perpendicular to the sapphire {1010} family of planes and the other
perpendicular to the {1120} family. These lead to GaN cantilevers that grow outward in
the [1010] and [1120] directions, respectively [7].

A detailed description of the metalorganic chemical vapor deposition (MOCVD)
growth conditions for ELO have been previously reported [6] and were used for the CE
growths. The resulting structures consist of a 250 Å LT-GaN nucleation layer, 0.4 μm
GaN grown at 1050 °C, and the cantilevers grown at 1100 °C. Results from two sample
types will be described: one grown just past coalescence to a total GaN thickness of 0.9
μm and another that has grown for a more extended time to a thickness of 2.2 μm. Samples were characterized using scanning electron microscopy (SEM), transmission
electron microscopy (TEM), atomic force microscopy (AFM), and cathololuminescence (CL).

Figure 1 presents an SEM image showing four and a half cantilever spans (2.2 μm thick), each 8.4 μm wide, over a 2.1-μm-deep trench, suspended between 2.8-μm supports. Both the top and bottom surfaces of the cantilever are essentially flat with the cantilever tilt being ≤ 0.1°, as determined by atomic force microscopy (AFM). Although a notch is present at the lower interface of two converging cantilevers just after coalescence (Fig 2), the notch is absent in this thicker growth. It is possible that the notch is filled in as growth continues, possibly by the evaporation and redeposition of the GaN deposited in the trench before coalescence, or it may not have been present initially. In ELO and PE, a void that corresponds to the CE notch is observed just above the dielectric mask at the coalescence front even after the growth of thick (several-μm layers), and a high density of TDs is observed above the void. In contrast, a significant portion of the coalescence front in CE appears to be free of TDs, as observed by cross-section TEM (Fig 2) on the barely coalesced samples with notches and by CL on the planar surface of thicker samples without notches (Fig. 3).

**Figure 1.** SEM micrograph of cantilever epitaxy.

**Figure 2: Cross-section TEMs of cantilever epitaxy: weak beam g=[1\ 1\ 2\ 0].**

The relative areas of exposed GaN and dielectric mask, or fill factor, profoundly affect the growth rates in ELO [6,8,9]. The reduced consumption of reactants over the dielectric mask due to selective nondeposition results in an increase reactant supply and enhanced rates in regions with large dielectric/GaN ratios. Additionally, the lateral
growth rate in a given region slows with time as the overgrown GaN occupies an increasing areal fraction. In contrast, CE involves GaN-on-GaN growth during the entire growth of the cantilever. Consequently, reactant supply and concomitant growth-rate variations should not occur and no “fill-factor” effects are expected. Figure 4 compares the growth from a 4-µm support over an 8-µm trench with the growth from a 16-µm support over a 4-µm trench. There is less than a 10% difference in thickness between the two. A pronounced dependence of tilt on fill factor is seen in ELO [10]. The CE surfaces inspected to date appear essentially flat after coalescence.

Figure 3. CL image of planar-substrate GaN grown at 1100 °C (left) and of GaN grown by cantilever epitaxy (right) showing absence of TDs (dark regions) in the cantilevers and along much of coalescence front (arrows).

There does not appear to be a strong dependence on the final appearance of CE-grown GaN that was initiated from either the \{1\bar{1}20\} or \{10\bar{1}0\} GaN planes (Fig. 5). Based on the relative amounts of GaN deposited at the center of the trench (0.6 vs. 0.8 µm for \{1\bar{1}20\} or \{10\bar{1}0\} GaN, respectively), an upper limit of a factor of 2 difference in rate appears to exist after subtracting the 0.4 µm deposited before lateral growth was initiated. Strong dependence on growth direction is observed in ELO (2).

Figure 4. Effect of relative support and trench sizes in CE from \{1\bar{1}20\} GaN planes.
The relative density of threading dislocations is a crucial issue in GaN growth. Figure 2 presents cross-section TEM images of three sites shortly after coalescence. No vertical TDs are observed in the cantilevers. In addition, there is a reduced number of vertical TDs over the edges of the supports. TDs in these edge regions turn over and run horizontally into the cantilevers. Similar turning of TDs into lateral growth regions has been reported in ELO [11] and LOFT[5]. Since TDs propagating perpendicular to the growth front may have reduced dislocation energies [5], this may account for the lower vertical TD density in the edge regions. The horizontal TDs all appear below the coalescence point at the top of the notches. No vertical TDs are observed at the coalescence front over two of the notches in Fig. 3. TEM, AFM, and CL (Fig. 3) measurements all indicate that a significant portion of the coalescence fronts appear to be free of vertical TDs. As with TEM, CL shows an increase in brightness above the 0.5-1 μm edge region of the support, consistent with a reduction in TD density [12]. This is in marked contrast with ELO, where a high density of TDs occur at the coalescence front and an increase in TD density at the mask edge is observed by CL, TEM, and AFM [1].

Figure 5. Comparison of CE growth from \{11\bar{2}0\} or \{10\bar{1}0\} GaN planes.

The transition zone from a support into a cantilever is shown in the AFM image in Fig. 6. On the left, one sees the wide (up to 0.5 μm), parallel steps of the cantilever, where the step-flow growth that is characteristic of the high cantilever growth temperature has proceeded without any step pinning by TDs. Such wide individual steps are consistent with the low degree of tilt (≤0.1 °) and are in marked contrast to the much narrower step widths (<0.1 μm) seen in AFM of ELO surfaces [1].

Over the center of the support (right), the penetrations of mixed-character TDs (b=1/3<11\bar{2}3>) at the surface are manifest as dark spots [13] corresponding to depressions and by the pinned steps that terminate at the dark-spot TDs. This is the typical appearance of GaN grown on conventional planar substrates [13]. Intermediate between these two regions is the support edge, a region between 0.5 and 1 μm wide where a reduced number of mixed TDs are still seen to penetrate the surface and pin steps. In larger-area AFM scans (Fig. 7), the angles of the steps in the cantilevers with respect to the original etched sapphire facet appear to be determined by the step-pinning at TDs in the edge region and are not constrained to a specific angle.
Figure 6. AFM image showing cantilever and support: composite of adjacent 2x2 μm scans.

Figure 7. AFM scan of a 12x12 mm CE region with 4-μm supports and 4-μm trenches.

The advantages of epitaxial growth of moderately lattice-mismatched cubic material systems, e.g., SiGe on Si, on reduced substrate areas have been previously described [14]. The nanometer-scale features that commensurate growth of materials with such extreme lattice mismatches as GaN and AlO₃ (16%) would seem, at first thought, to make this approach unfruitful. However, the extreme mismatch produces
growth that is not truly commensurate, but rather the wurtzite Al₂O₃ appears merely to provide an orientational template for subsequent GaN growth. In fact, in-situ measurements of the strain in GaN during actual growth on planar Al₂O₃ (0001) have shown that GaN grows with only slight tensile stress at a growth temperature of 1050 °C [15]. Although nm-scale features would be necessary to reduce TD densities in commensurate growth, μm-scale features suffice for mere orientational templating. The relatively TD-free regions within 0.5 to 1 μm of the support edge suggest that further reduction of supports from the 3-μm to 1-μm range should produce appreciable reduction of TDs above most of the support regions.

In summary, cantilever epitaxy provides an easier way to produce reduced-dislocation-density GaN than have previous lateral overgrowth techniques. The process yields almost dislocation-free cantilever spans. It also yields lower threading dislocation densities both at the coalescence front and at the initiation region of lateral growth than have been obtained with lateral overgrowths on dielectric masks. Pronounced reductions in dislocation densities near the support edges suggest that further improvements in the process may produce a “GaN substrate” with very low dislocation densities over the entire surface.

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