Characterization of (Al,Ga,In)N grown using Lateral Epitaxial Overgrowth

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Summary Abstract

We describe the effect of various growth parameters such as V/III ratio and temperature on the lateral epitaxial overgrowth of GaN by MOCVD. We also discuss the effect of the mask pattern geometry used as the "seed" template. Structural characterization (AFM, TEM) show that for suitable growth conditions the LEO GaN contains almost no threading dislocations ($\sim 10^5$ cm^{-2}). Based on these results we developed a 40 μm period LEO GaN template (containing essentially dislocation-free regions ~15μm wide) that is suitable for the subsequent growth of device layer structures and device fabrication. Preliminary results showing the improved properties of AlGaN/GaN and InGaN/GaN heterostructures grown on these templates are then discussed.

Introduction

The lateral epitaxial overgrowth (LEO) technique is essentially a selective area regrowth process shown schematically in figure 1. First, we grow a GaN template on sapphire by MOCVD. Due to the large lattice mismatch with the substrate, the epilayer contains a high density of threading dislocations that are detrimental to the properties of subsequently grown device layers. A suitable mask material is then deposited and patterned using conventional processing techniques. (To date we have used primarily SiO_2 as a mask, although we have also tried SiN.) The wafer is then returned to the MOCVD reactor for regrowth. The exposed epilayer in the mask windows acts as a "seed" for the regrowth, which proceeds vertically and laterally. Most importantly the laterally overgrown material is dislocation-free under suitable growth conditions due to (1) the blocking of dislocations by the mask and (2) the interaction between dislocations and the free surface. With this technique, relatively large areas of dislocation-free material can be achieved.

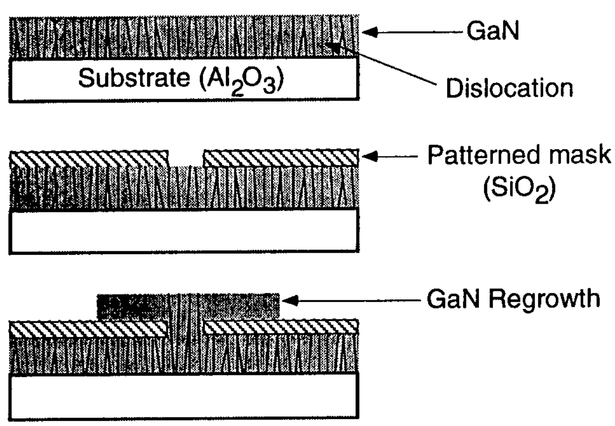

Figure 1. Schematic of lateral epitaxial overgrowth (LEO) technique.

LEO GaN Growth Optimization

For the period covered by this report, a large fraction of our research involved an investigation of the basic LEO process with an aim to optimize growth conditions suitable for device applications. As described in the next few sections, the properties of the LEO material are sensitive to the growth conditions such as pressure, temperature, and V/III ratio. After jumping around a wider parameter space early, the regrowths are performed at low pressure (76 torr). Due to crystal symmetry effects the overgrowth also depends on the geometry of the mask windows. With device applications such as FETs in mind we have mostly looked at regrowth on stripe patterns with a seed window width of 5 μm and period of 10-500 μm. Also, all results reported here have stripes aligned along <1$\underline{1}$00>$_{GaN}$ – we found early on that this orientation gives the fastest lateral growth.

V/III Effects

It turns out that LEO GaN is quite sensitive to the V/III ratio. We carried out a systematic experiment in which we varied the input TMG and NH_3 flows from 13.5-108 sccm and 900-3600 sccm, respectively, with the V/III ratio varying between 375-3055. The time of growth was adjusted so that the total Ga supply was kept constant at 810 sccm*minutes. The growth temperature was 1060 °C and we used H_2 as a carrier gas.

Qualitatively, varying the TMG and NH_3 flows has a dramatic effect on the morphology of the LEO GaN. Figure 2 shows cross-sectional SEM images of the LEO material for various input flows. In this case the mask pattern is 5 μm stripes separated by 15 μm.

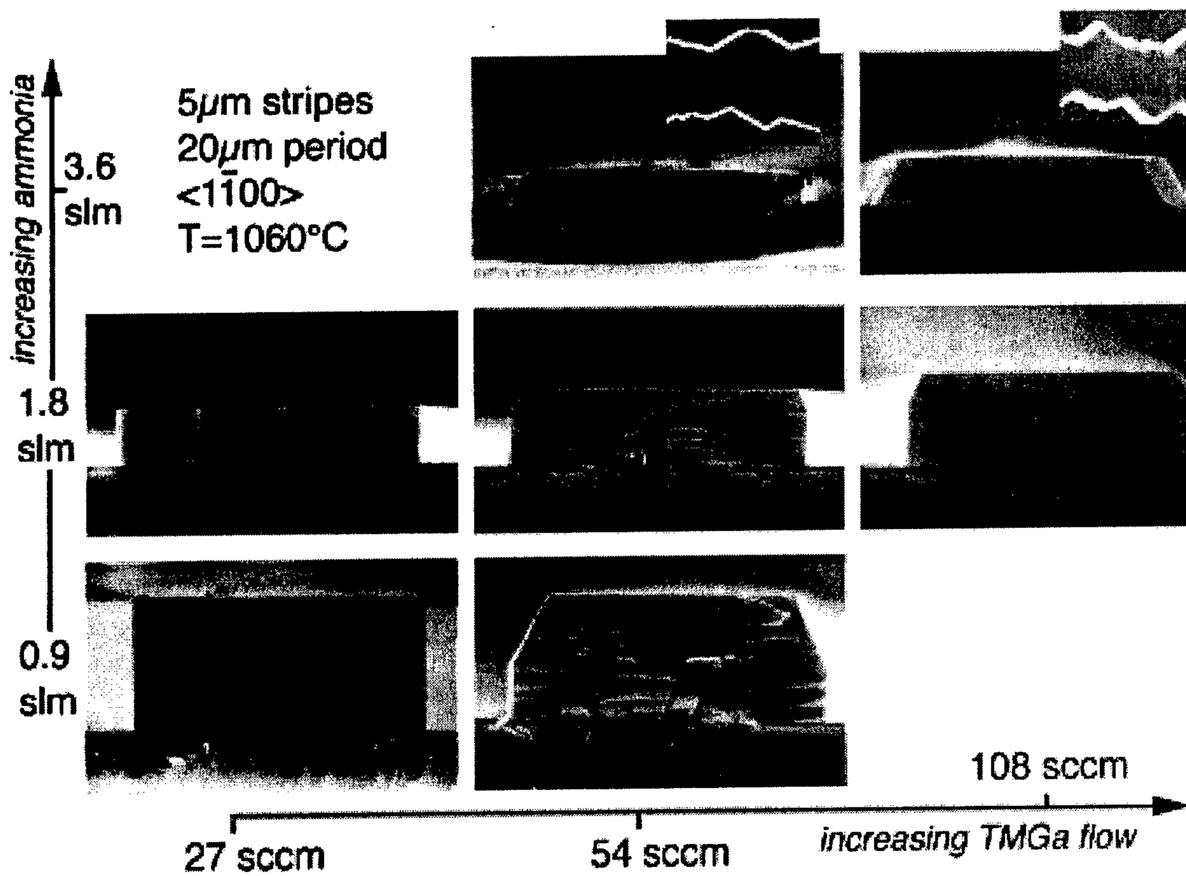

Figure 2. Cross-sectional SEM images showing effect of TMGa and NH_3 flows on LEO GaN morphology for growth on stripes aligned along a <1$\underline{1}$00> direction.

The overgrowth may be bound by a number of different crystallographic facets: the basal (0001) plane; {11$\underline{2}$0} planes, which are parallel to the stripes and correspond to vertical sidewalls; inclined {11$\underline{2}$n} planes, where n~2, which are also parallel to the stripes; and inclined {1101} planes, which are faceted at 30° to the stripes and which correspond to jagged sidewalls. Broadly speaking, high V/III ratios lead to jagged sidewalls, moderate V/III ratios lead to vertical sidewalls and low V/III ratios lead to the inclined sidewalls. At this time it is not clear whether thermodynamics (i.e. surface energies) or kinetics (i.e. planar growth rates) determine the most favorable facets for a given V/III ratio.

Our SEM analysis also revealed that the lateral and vertical growth rates are dependent variables subject to the constraint that the total volume of deposited material is a constant over our range of input flows. The lateral growth rate generally increases with increasing V/III ratio, although it tends to saturate once the jagged sidewalls appear. As shown in figure 3, we found that the partial pressure of NH_3 is more important than the partial pressure of TMGa in this respect, with the lateral growth rate increasing dramatically above a critical NH_3 flow.

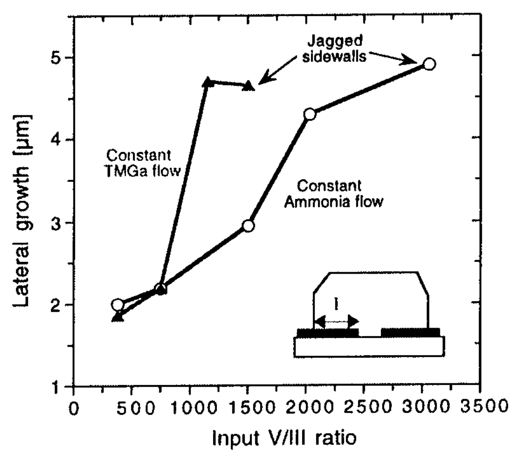

Figure 3. Effect of V/III ratio on LEO GaN lateral growth rate.

Fill Factor Effects

In general, we have found that the regrowth is highly selective with no observable growth occurring on the mask areas between the LEO. Evidently, any material landing on the mask is able either to migrate to the LEO growth front or to re-evaporate. A SEM analysis of samples grown with various stripe patterns shows that the former occurs except for very large stripe spacing. Figure 4 is a plot of the normalized volume as a function of the pattern fill factor, *f*, which is defined as the fraction of mask area etched away for regrowth (so smaller f corresponds to a larger

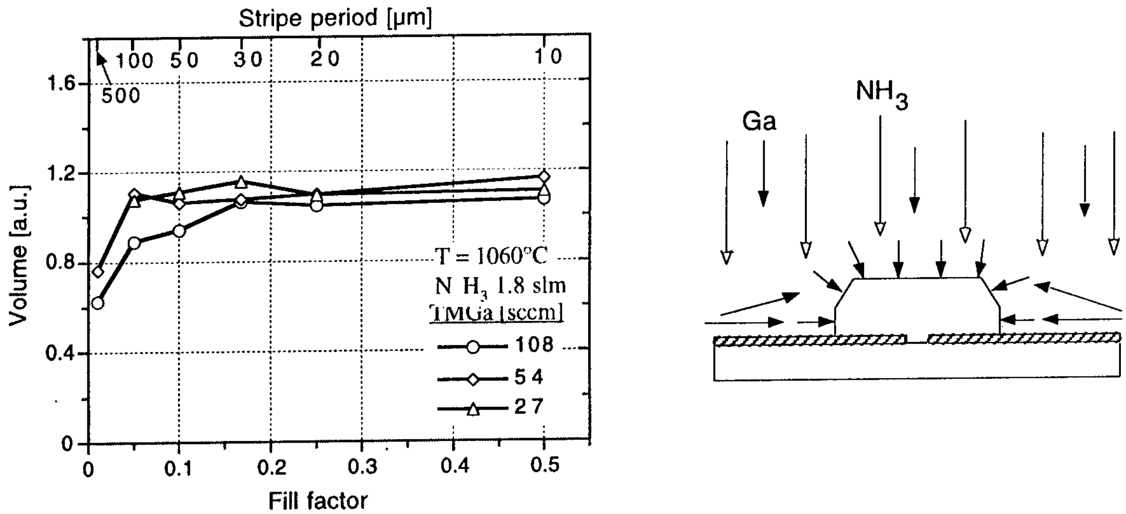

Fig. 4(a) Plot of net volume of growth as a function of mask stripe fill factor. (b) Schematic representation of enhanced supply of Ga from the mask regions that leads to a fill factor-dependent local V/III ratio at the growth front.

period). Up to a critical stripe period we found that the net volume growth rate is equivalent to the planar growth rate on an unpatterned template. For a fixed NH_3 partial pressure, the critical stripe period increases with decreasing TMGa flow as expected for growth limited by the group III species. We concluded that the supply of Ga from the mask effectively reduces the *local* V/III ratio at the growth front and all Ga atoms are incorporated until there is insufficient NH_3 (or active N species) to stabilize the crystal (i.e. the growth becomes group V limited). This conclusion was borne out by two other observations:

(i) morphology – for a given growth run the inclined sidewalls become more pronounced at lower fill factors, as shown in figure 5.

(ii) relative growth rates – the lateral-to-vertical growth ratio increases with increasing fill factor in agreement with the data in figure 3.

Growth Temperature Effects

We also examined the effect of growth temperature. As shown in figure 6, the effect of raising the temperature is essentially the same as increasing the V/III ratio – more lateral growth and more vertical sidewalls. In fact, we believe that the V/III ratio really is increasing due to more efficient cracking of the NH_3 at higher temperatures.

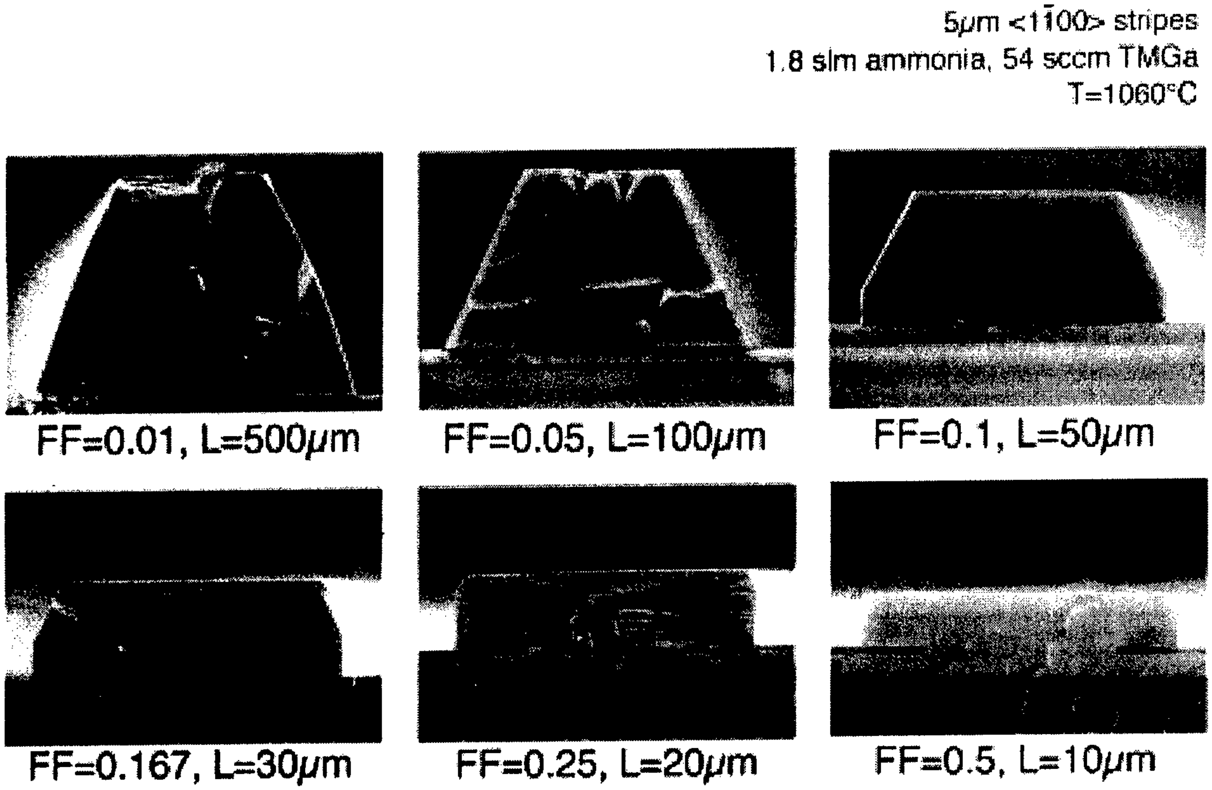

Figure 5. Cross-sectional SEM images showing effect of fill factor on LEO GaN morphology. Note the gradual trend from inclined to vertical sidewalls with increasing fill factor.

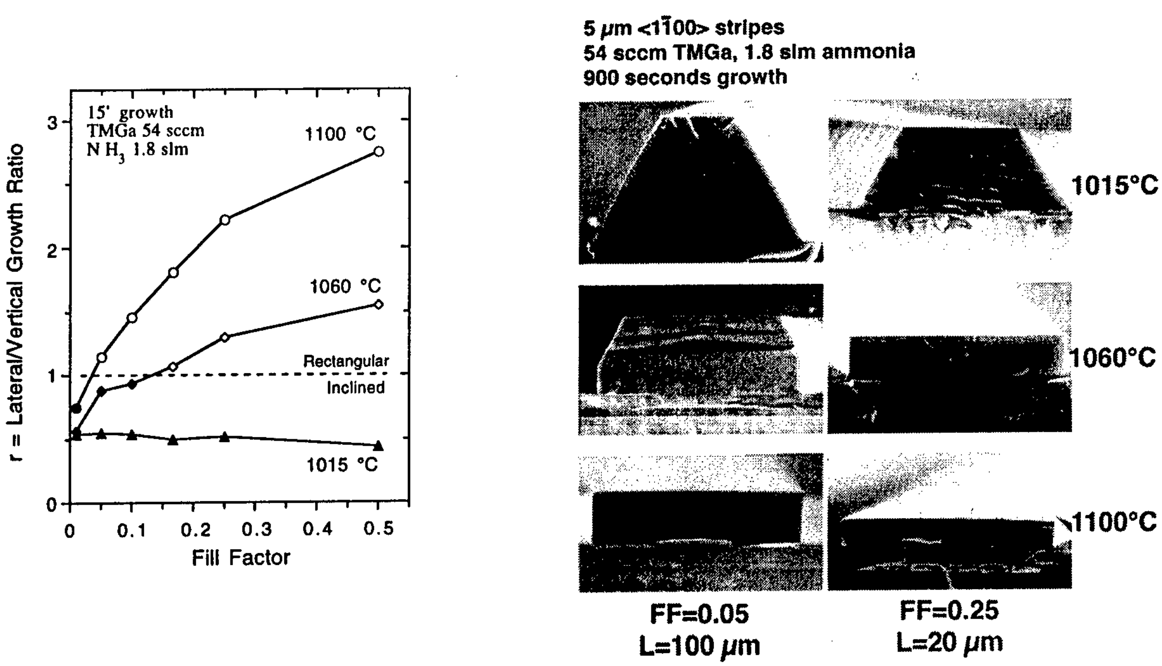

Figure 6. Effect of temperature on (a) lateral-to-vertical growth ratio and (b) LEO morphology.

Structural Characterization

We have performed structural characterization (x-ray, AFM, TEM) to confirm the improved crystal quality of the LEO GaN. Figure 7 shows transmission electron micrographs of typical LEO stripes. The dislocation density in the LEO GaN is reduced 2-3 orders of magnitude from the ~10^9 cm^{-3} in the bulk GaN regions. We do observe a relatively high dislocation density above the edge of the mask opening. These dislocations, which lie mostly in the (0001) plane, are related to the fact that the LEO wing is tilted down with respect to the region over the mask opening by ~0.5-1°. The origin of this tilt is unclear at this time, but it leads to a grain boundary where adjacent LEO regions coalesce, as shown in the plan view TEM image in figure 7(b).

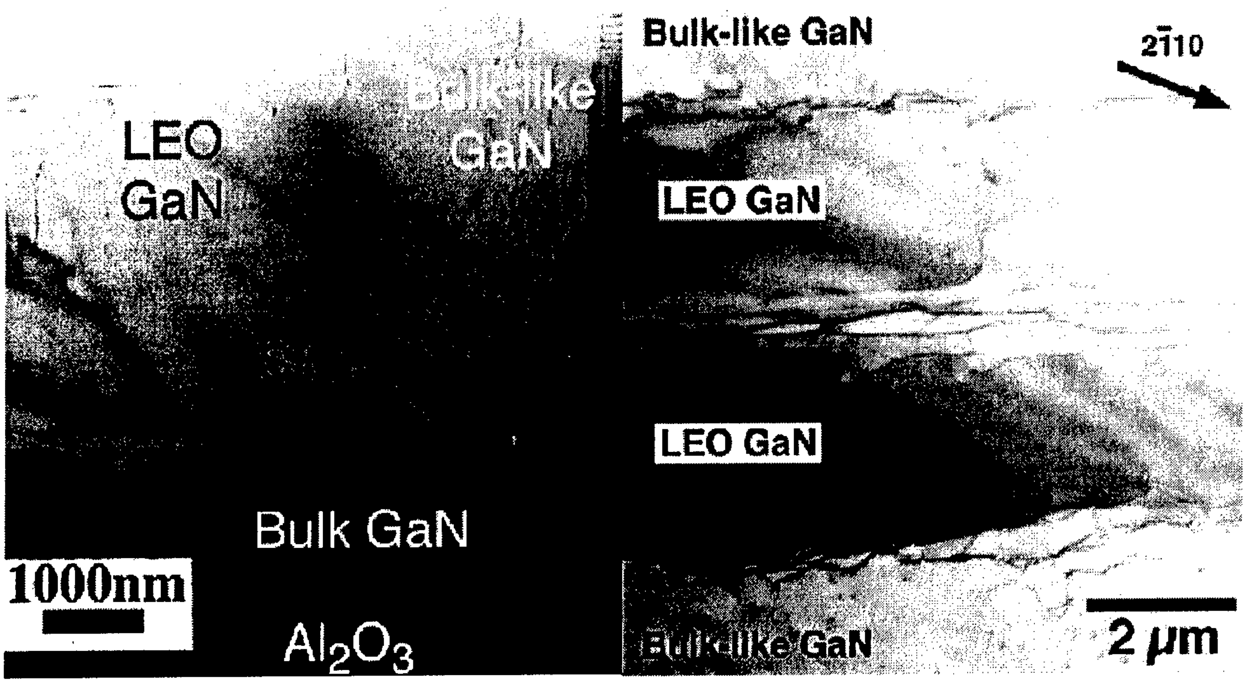

Figure 7. Cross-section transmission electron micrograph of LEO GaN stripe. Note near absence of dislocations in the LEO region above the SiO_2 mask compared to the bulk GaN regions. (b) Plan view of coalesced LEO film. Note dislocations lying in the plane of the film near the LEO/bulk interface and at the intersection between adjacent LEO stripes.

AFM also confirms the near absence of threading dislocations intersecting the (0001) growth surface in the LEO regions, as shown in figure 8. Many of the dislocations have a mixed screw character that leads to step-edge termination and creation on a bulk GaN surface. In contrast, the step edges on the LEO GaN are not pinned and we have observed that they tend to lie along specific crystallographic directions as a result.

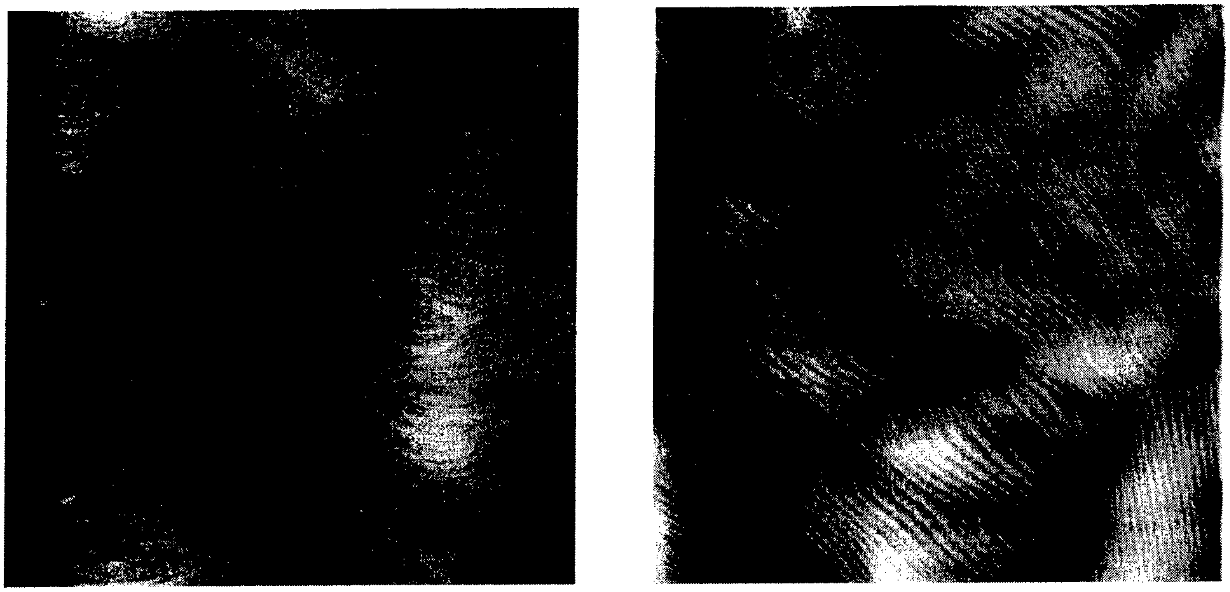

Figure 8. AFM images of (a) bulk GaN and (b) LEO GaN surfaces. Threading dislocations appear as small black pits. Note the step arrays on the LEO GaN surface. Image size is 8x8 μm in both cases.

LEO Templates for Device applications

There are two approaches to obtaining sufficiently large areas of dislocation-free GaN via LEO suitable for device applications. These are shown in figure 9. The first approach involves relatively short pattern periods and growing until the LEO regions coalesce. The patterning and regrowth process is then repeated so that the final layer is dislocation free everywhere. We have found there are severe problems with this approach, namely voids and dislocations at the interface (see figure 7 above).

The second approach is to regrow using a patterned mask with a low fill factor and grow until there is sufficiently large overgrowth area. In this case some important issues are (i) taking into account the increased growth rate due to Ga supply from the mask, and (ii) finding growth conditions that give a fast lateral growth rate so that the growth time is reasonable. Based on our earlier studies of the temperature and V/III effects, we have developed a 40μm period LEO technology that requires approximately 3 hours growth time to achieve ~15 μm wide wings of dislocation-free LEO GaN. This is sufficiently wide to allow fabrication of devices such as FETs, pn junction diodes and photodetectors.

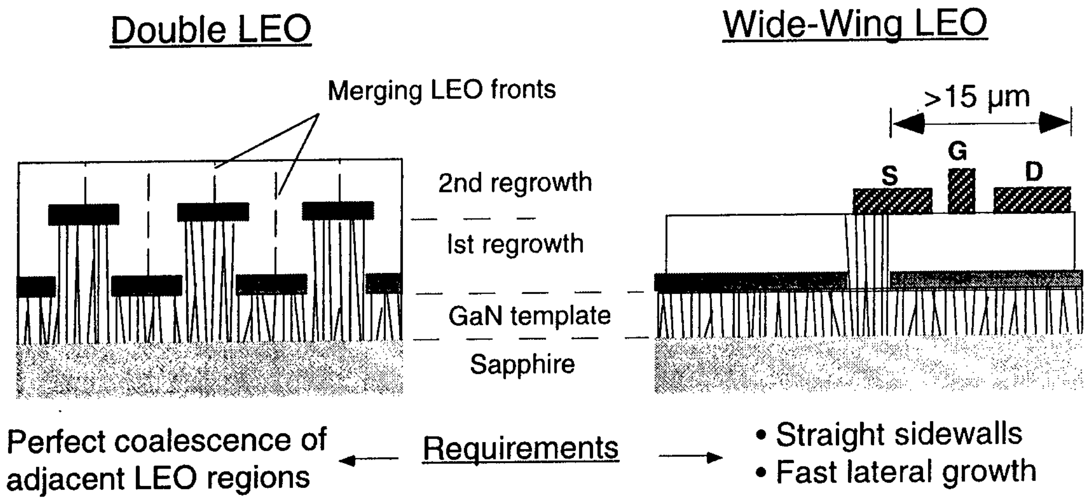

Figure 9. Schematic representation of two approaches to achieving large areas of LEO GaN suitable for subsequent device fabrication.

AlGaN/GaN Heterostructures Grown on LEO

We have grown AlGaN/GaN heterostructures suitable for FETs on the wide-wing LEO templates described above. Figure 10 is a composite image of the surface morphology of such a structure taken using AFM. Note the dramatic improvement in the quality of the AlGaN growth in the LEO region related to the absence of threading dislocations. (It is hoped that this will open up the available growth window for high quality AlGaN.) The electrical characterization of FETs fabricated on this material is in progress. Initial results indicate that the gate leakage current is at least an order of magnitude lower when the gate is placed over a dislocation-free region compared to gates on standard material. Another interesting result was that we found that our normal insulating GaN buffer layer remained insulating on LEO, thereby proving that dislocations are not necessary to compensate the unintentional shallow dopants typically observed in GaN.

InGaN/GaN quantum wells grown on LEO

We have also made some initial studies of InGaN quantum wells grown on LEO material to see what effect removing the dislocations has on the optical properties of such wells. As shown in figure 11 the luminescence is much more uniform in QWs grown on LEO GaN due to the absence of non-radiative recombination at dislocations. However, time-resolved photoluminescence experiments show that the lifetime of carriers is not affected by growth on LEO suggesting that the diffusion length of carriers in InGaN QWs is shorter than the typical dislocation spacing in normal GaN

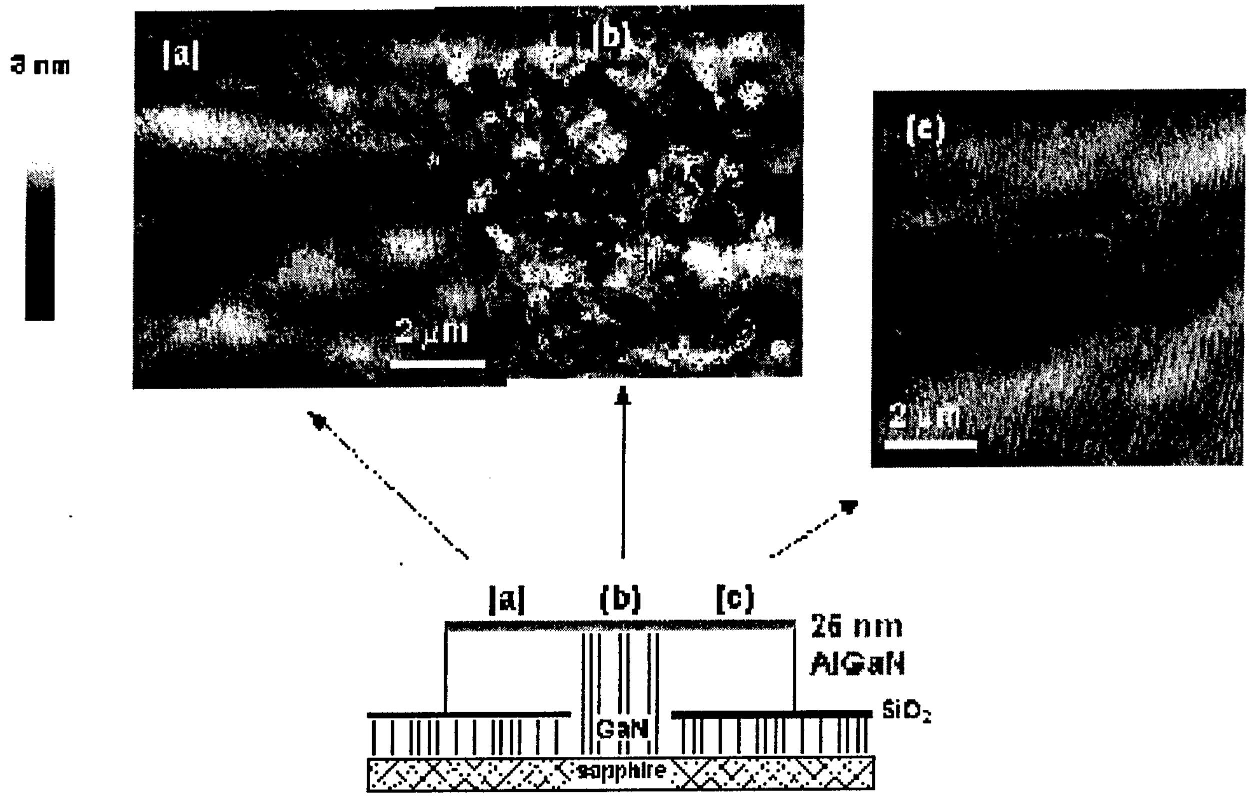

Figure 10. AFM images showing surface morphology of AlGaN/GaN FET. Schematic shows position of images relative to LEO mask region. Note the very rough AlGaN caused by the threading dislocations present in the bulk-like GaN region and the smooth, uniform step arrays in the dislocation-free LEO region.

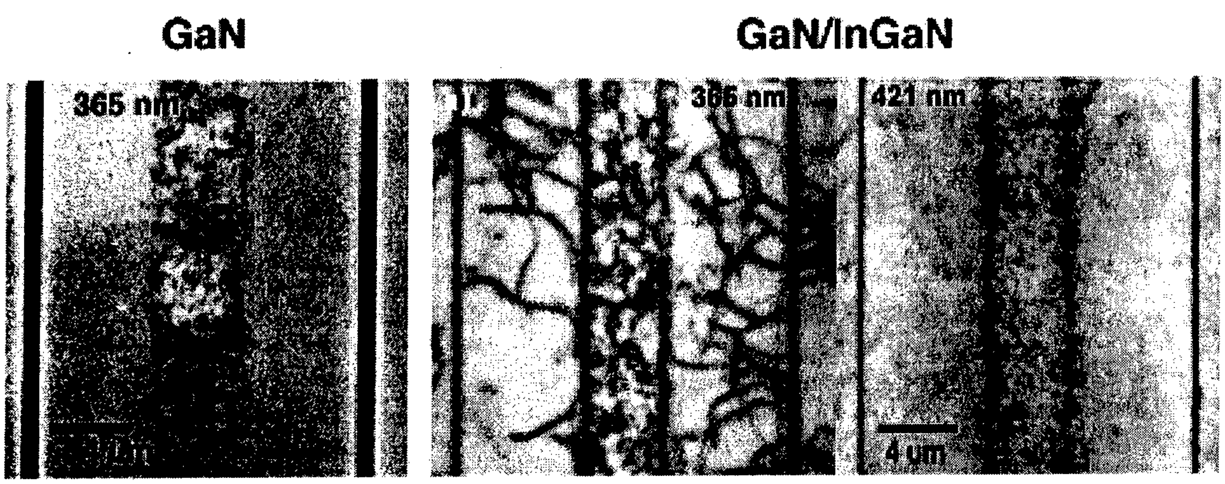

Figure 11. Cathodoluminescence images of bulk GaN and InGaN/GaN quantum wells grown on a LEO stripe (plan view). Note the dark mottling in the regions over the original mask opening due to non-radiative recombination associated with dislocations. Individual, lateral threading dislocations are also observed in the GaN underlying the InGaN QW (middle picture). These are related to poor coalescence of adjacent LEO stripes. Note that these dislocations do not propogate in the vertical direction as they are not visilbe in the QW itself (right picture).

Unresolved Issues and Future Work

There are some important unresolved issues with our LEO GaN at this time. The first is that of auto-doping. Electrical characterization of the LEO GaN suggest it is n-type, although Hall measurements have not been performed yet due to their difficulty on such a small scale. One known problem with the SiO_2 mask is that it etches during growth and presumably is responsible for auto-doping the LEO material. To avoid this problem we are trying alternate masks. First we tried PECVD-SiN but there was no appreciable overgrowth of this material (probably due to contamination problems). We are now using SiN deposited at high temperature in the MOCVD reactor itself. Other groups have reported success using this technique.

Another issue is that of device fabrication on non-coalesced wide-wing LEO. Due to lateral-to-vertical growth rates of ~2, the thickness of the LEO region can be quite large and planarization has proven to be difficult. Thus it seems necessary to grow to coalescence. However, there tend to be voids at the coalesced interface that appear to act as stress concentrators (the lateral threading dislocations observed in figure 11 seem to be associated with voids). It therefore appears desirable to coalesce LEO regions with inclined sidewalls, which should eliminate the void problem.

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