Detrimental effects of dislocations II

Band diagram around a charged dislocation

If the Fermi level is above the dislocation induced acceptor states in the forbidden gap, then they will capture electrons and get charged. The bands will look like a cone around dislocation in 3D.
3D image of the dislocation band diagram

- Three dimensional image of conduction band bending around the dislocations in an AlGaN/GaN heterostructures measured by scanning Kelvin probe microscopy (SKPM)
Detrimental effects of dislocations: Summary

- Dislocations cause leakage current in schottky contacts by acting as electrical short (electrons move from state to state)
- Dislocations get charged by capturing electrons. Effect....
  - Reduction in sheet charge at the interface
  - Reduction of electron mobility
- Dislocation states act as non-radiative recombination centers for electrons and holes and reduce the luminescence efficiency for opto-electronic devices
- Dislocations also cause lifetime and reliability problems in devices due to over-heating

Solution to the problems created by dislocation .......
Get rid of them!
Major techniques to reduce dislocations

• Bulk growth
  – By direct synthesis (from Ga metal and nitrogen)
  – By sublimation (by using GaN powder as starting material, and by vapor transport of Ga, which later reacts with NH$_3$)

• Exotic substrates
  – Si
  – ZnO
  – Lithium niobate
  – Lithium gallate

• Lateral epitaxial overgrowth (LEO) or epitaxial lateral overgrowth (ELO)

• Pendeco-epitaxial growth (pendeco means suspended)

• Quasi-bulk growth by HVPE on sapphire
Reduction of dislocations: LEO growth

1. 
   - One of the most commonly used techniques to reduce dislocation density in nitride films (both c-plane and a-plane)
2. 
   - Advantage: Simple fabrication procedure, can be easily implemented
3. 
   - Disadvantage: Dislocation density only reduced in selected areas. The stripes free of dislocation not very suitable for large scale device fabrication

Cross-sectional TEM image of LEO GaN
• Strategy (take GaN by MOCVD as example): selectively mask a GaN film; regrow through openings and over mask

**Patterning**

**PECVD**
- Wet etching
- 5 μm stripes
- spacing 5-500 μm

**LEO growth**

**LP-MOCVD**
- TMG, NH₃
- 5 μm/hr nom.
- 1015-1100°C
Stripe Morphology

- Stripe orientation is an important parameter:
Stripe Morphology (cont.)

- V/III ratio strongly affects morphology (the highlighted is chosen to be the standard growth condition):
SEM of <1100> LEO

Fill factor dependence
(FF = window width / repeat period)

{1120} sidewalls preferred at higher FF’s

Growth condition:
T=1065°C, f(NH₃)=1.8 slpm
Coalesced LEO - TEM

After optimization…
• Few dislocations formed at coalescence front
• Formation of *in-plane twist* boundary: ~ 0.02°
LEO - AFM

- No threading dislocation terminations visible at coalescence front

5 μm
vertical range: 3 nm

Fig. 4.18 Plan-view Nomarski-contrast optical micrographs of step bunch (terrace) formation at coalescence fronts of stripes with 20 μm (left) and 40 μm (right) repeat periods.

(a)
(b)

Step bunching...life is not perfect...
**Reduction of dislocations: Pendioepitaxy**

**Advantage:** Reduces dislocations in GaN film over the entire area

**Disadvantage:** Requires lithographic patterning and RIE etching step. This may result in stress in the GaN film. Also, the material has lower mechanical strength.
etch and regrowth without mask ➔
Maskless or cantilever epitaxy

Nano heteroepitaxy (NHE)

In-situ dislocation reduction

Fig. 4.73 Simplified schematics of maskless LEO process flow using PR (left column) and SiO₂ (right column) as etch mask in RIE step.

Fig. 4.79 Montage of AFM images for a stripe in contact with sapphire, showing wing (overgrown) region on left and seed region on right. The total z-range is 2 nm. Note that vertical lines are scan artifacts.

Fig. 3 Cross-sectional bright-field (BF) TEM image of the GaN over-layer/GaN buffer-layer structure on a SiC substrate. Note that the dislocation density is drastically reduced at the interface that is modified by an anti-surfactant.

Fig. 1. (a)–(d) AFM micrographs of the surfaces of GaN grown on AlGaN surface with various amounts of applied TES. (a) no TES, (b) 3.2 mmol, (c) 8.1 mmol, and (d) 32 mmol. Note that the growth mode is changed from step-flow in (a) to three-dimensional in (b). Figures (b) and (c) show fractional-dimensions because of the presence of nano-holes. The circle indicated in (d) is the area that is magnified in Fig. 2.
Quasi-bulk GaN: Hydride Vapor Phase Epitaxy

Ga (melt) + HCl = GaCl + \( \frac{1}{2} \) H\(_2\)

GaCl + NH\(_3\) = GaN + HCl + H\(_2\) (forward reaction)

GaN + HCl = GaCl + \( \frac{1}{2} \) N\(_2\) + \( \frac{1}{2} \) H\(_2\) (reverse reaction)

“Hydride (not halide)” because of the use of NH\(_3\). If NCl\(_3\) is used then it becomes “Halide”

- Usually requires MOCVD templates or LEO substrates (not easy to grow smooth layers just by itself)
- Usual growth rates few tens of microns per hour resulting in rougher but low dislocation density films
- Low cost technique
Morphology of HVPE GaN

- The HVPE GaN film (300 micron thick) was grown on sapphire.
- Free carrier concentration is $8 \times 10^{15} \text{cm}^{-3}$ and mobility of 350 cm$^2$V$^{-1}$s$^{-1}$.
- Dislocation density of $10^7$ cm$^{-2}$, which is much lower compared to that in MOCVD or MBE grown films.
- This film was used to grow homoepitaxial GaN by MOCVD and resulted in roughness of 0.2 nm and dislocation density of $2 \times 10^7$ cm$^{-2}$.
Devices on LEO: electronic devices

P-N Junction on LEO GaN
P-N Junction on dislocated GaN

Device Structure

Current (A)
Applied Bias (V)
Current Density (A/cm²)

Leakage Current [A] vs. Applied Bias [V]
Dislocations
Emitter
Base
Collector
Devices on LEO: optoelectronic devices

**InGaN based blue lasers**
- Reduction in threshold current for lasers on wings and coalescence fronts (from 8 to <4 kA/cm²)

**AlGaN/GaN based UV photo detectors**
- Over 7 order-of-magnitude reduction in dark current
- Wings, coalescence fronts: responsivity drops by 3 oom over 25 nm range