Investigation of the structural and electrical properties of $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ high electron mobility transistor structures cooled under $\text{N}_2$ and $\text{H}_2$ carrier gases

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Introduction
$\text{AlGaN}/\text{GaN}$ heterostructures are of great interest for the fabrication of high electron mobility transistors (HEMTs). The properties of these materials allow for the production of devices with high efficiency, power density, operating voltages and operating temperatures [1]. Nanoscale surface cracks have the potential to form during the growth process and appear to nucleate from dislocations [2]. These nanoscale surface cracks present a potential problem for the fabrication of HEMTs and may lead to a reduction in device efficiency and possibly device failure. Kotani et al in 2013 [3] showed that for $\text{Al}_{x}\text{Ga}_{1-x}\text{N}$ HEMT structures grown by low-pressure metal-organic vapour phase epitaxy (MOVPE) and cooled down under $\text{H}_2 + \text{N}_2$ nanoscale cracking was obtained, however no nanoscale surface cracks were observed if the $\text{H}_2$ was substituted by $\text{N}_2$. In the present work we have studied $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ HEMT structures grown on sapphire substrates with an $\text{AlN}$ nucleation layer [4] by low-pressure MOVPE cooled down under $\text{H}_2$ and $\text{N}_2$ carrier gases respectively. We have investigated the surface morphology and dislocation distribution by electron channelling contrast imaging (ECCI) and Hall/\text{van der Pauw} measurements were used to determine wafer electrical properties sheet resistance ($R_s$), mobility ($\mu$) and 2DEG carrier density ($n_{\text{2DEG}}$).

High Electron Mobility Transistors (HEMTs)

- A transistor is a semiconductor device which can act as an insulator or a conductor
- They can be used as switches or amplifiers, and are in every electronic device
- Traditional structure is Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)
- Most commonly fabricated on Si
- A voltage is applied at the gate and source contacts, which generates an electric field through the oxide layer, which leads to the creation of an inversion channel
- Current flows from the source to the drain though the inversion channel
- HEMTs have a similar operating principle to MOSFETs
- Current flows from the source to the drain via the 2-dimensional electron gas (2-DEG)

Nitride HEMTs

- Fabricated from 2 nitride semiconductor materials with different band gap energies
- Nitride HEMTs do not require doping to generate a 2-DEG
- 2 DEG arises due to polarisation difference between layers
- Spontaneous polarisation – intrinsic to the material and arises due to the wurtzite crystal structure
- Piezoelectric polarisation – arises due to the difference in lattice constants between the layers
- Larger polarisation difference leads to a larger 2-DEG density
- Larger 2-DEG density leads to higher device efficiency

AlGaN/GaN HEMTs

- $\text{AlGaN}/\text{GaN}$ HEMTs have high 2-DEG densities
- Spontaneous polarisation in wurtzite crystal structures can lead to an electric field of up to 3 MV cm$^{-1}$
- Piezoelectric polarisation in $\text{AlGaN}/\text{GaN}$ heterostructures can generate an additional 2 MV cm$^{-1}$
- $\text{AlGaN}$ layer is under tensile strain due to lattice mismatch with $\text{GaN}$
- High breakdown voltages – good for power electronics applications
- Large heat capacity – good for high temperature operation
- Large power density – more power output or smaller device size

Electron Channelling Contrast Imaging (ECCI)

- Rapid non-destructive method for
- Revealing sub-grain structure
- Imaging dislocations and determining dislocation density, type and distribution
- Revealing atomic steps
- Resolution of tens of nanometres
- Can be used in conjunction with Secondary electron imaging
- Electron backscatter diffraction
- Cathodoluminescence
- Electroluminescence
- WDX & EDX

Sample Structure and growth details

$\text{Al}_{0.2}\text{Ga}_{0.8}\text{N}/\text{GaN}$ HEMT structures were

- grown by low-pressure MOVPE
- grown on sapphire substrates with an $\text{AlN}$ nucleation layer
- cooled down under either $\text{H}_2$ carrier gas or $\text{N}_2$ carrier gas

Sample Structure and growth details

- $\text{Al}_{0.2}\text{Ga}_{0.8}\text{N} (= 15 \text{ nm})$ / $\text{GaN} (= 1 \mu \text{ m})$
- $\text{N}_2$ cooled – nanoscale surface cracks
- Sub-grains revealed by changes in grey scale
- Dislocations located on sub-grain boundaries
- Ratio of pure edge dislocations to those with a screw component = 2:1

Electrical Results

<table>
<thead>
<tr>
<th>Cooling</th>
<th>$R_s$ (Ohm/square)</th>
<th>$\mu$ (cm$^2$/V.s)</th>
<th>$n_{\text{2DEG}}$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{H}_2$</td>
<td>983</td>
<td>985</td>
<td>6.40 x 10$^{12}$</td>
</tr>
<tr>
<td>$\text{N}_2$</td>
<td>904</td>
<td>996</td>
<td>6.93 x 10$^{12}$</td>
</tr>
</tbody>
</table>

The table above summarises the samples’ electrical properties. Note that they are very similar, so the cracks do not appear to unduly influence the electrical properties, indicating that the cracks do not penetrate far into the AlGaN/GaN layer.

Summary: Combining SEM structural characterisation and electrical characterisation implies that the presence of nanoscale surface cracks may not be detrimental to the electrical characteristics of $\text{AlGaN}/\text{GaN}$ HEMTs.

References