Investigation of the structural and electrical properties of $Al_{0.2}Ga_{0.8}N/GaN$ high electron mobility transistor structures cooled under N_2 and H_2 carrier gases

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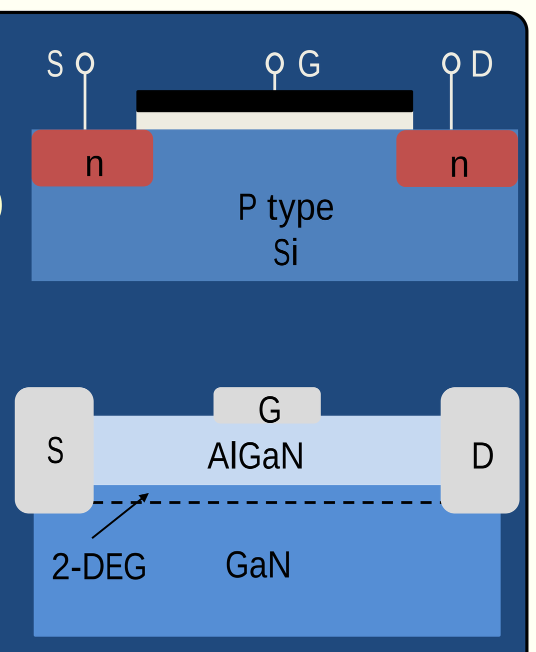
Introduction

AlGaN/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 $Al_{0.2}GaN_{0.8}$/GaN HEMT structures grown by low-pressure metal-organic vapour phase epitaxy (MOVPE) and cooled down under H_2 + NH_3 nanoscale cracking was obtained, however no nanoscale surface cracks were observed if the H_2 was substituted by N_2. In the present work we have studied $Al_{0.2}Ga_{0.8}N$(»15 nm)/GaN(»1 mm) HEMT structures grown on sapphire substrates with an AlN nucleation layer [4] by low-pressure MOVPE cooled down under H_2 and N_2 carrier gases respectively. We have investigated the surface morphology and dislocation distribution by electron channelling contrast imaging (ECCI) and Hall/van der Pauw measurements were used to determine wafer electrical properties sheet resistance (R_{sh}), mobility (μ) and 2DEG carrier density (n_{sh}).

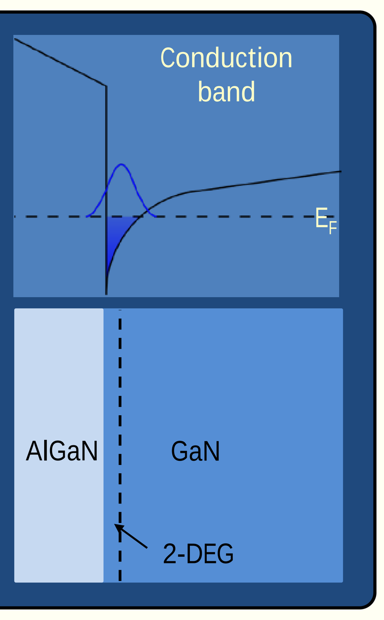
High Electron Mobility Transistors (HEMTs)

- 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 Trasnsistor (MOSFET)
- Most commonly fabricated on Si
- A voltage is applied between 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)



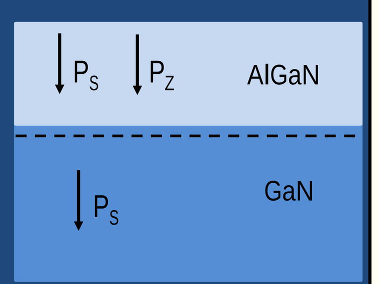
Nitride HEMTs

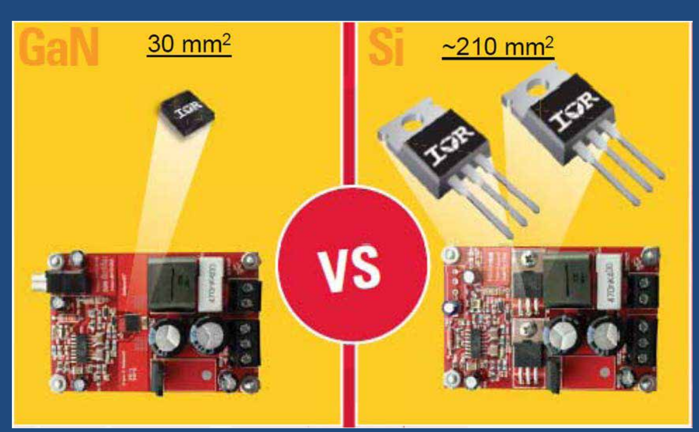
- Fabricated from 2 nitride semiconductor materials with different band gap energies
- Nitride HEMTs do not require doping to generate a 2-DEG
- 2-DEG arises due to polarisation difference between layers
  - Spontaneous polarisation – intrinsic to the material and arises due to the wurtzite crystal structure
  - 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

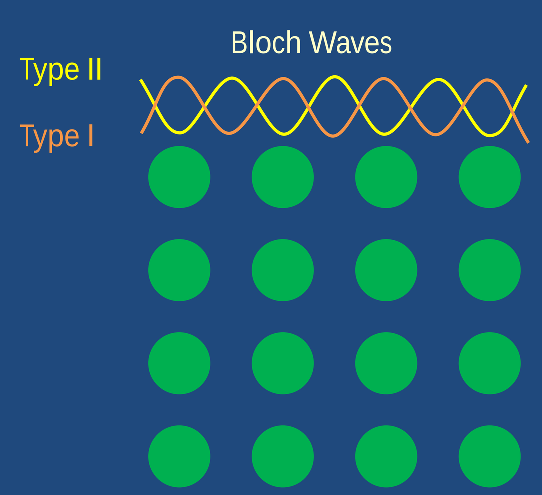
- AlGaN/GaN HEMTs have high 2-DEG densities
- Spontaneous polarisation in wurtzite crystal structures can lead to an electric field of up to 3 MV cm^{-1}
- Piezoelectric polarisation in AlGaN/GaN heterostructures can generate an additional 2 MV cm^{-1}
- AlGaN layer is under tensile strain due to lattice mismatch with 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

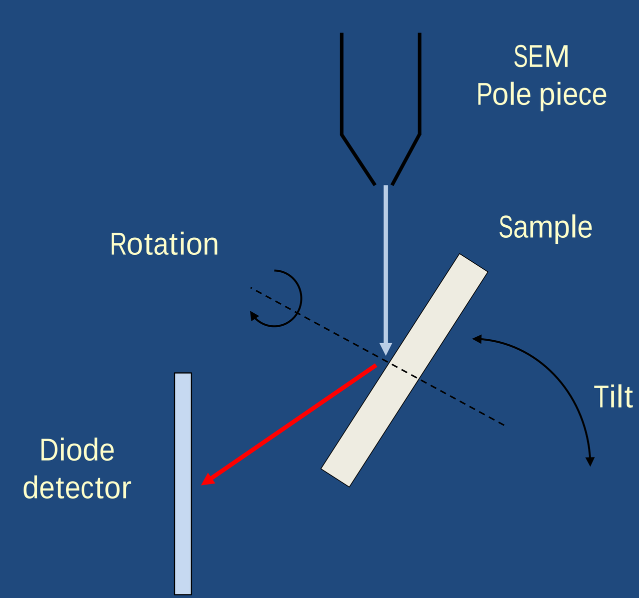


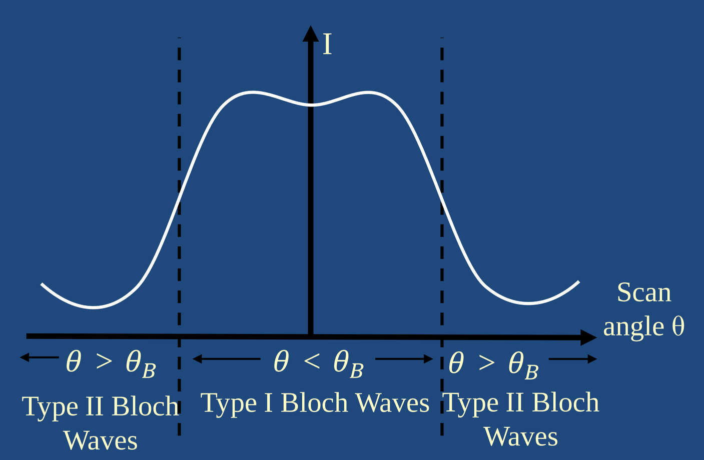


Electron Channelling Contrast Imaging (ECCI)

ECCI is a scanning electron microscope technique which uses diffracted backscattered electrons (BSE) to image tilts, twists and the strain field associated with extended defects in the atomic structure of a material.
The intensity of the BSEs is strongly dependent on the angle of incidence of the electron beam. The intensity of the BSE can be represented using Bloch waves.







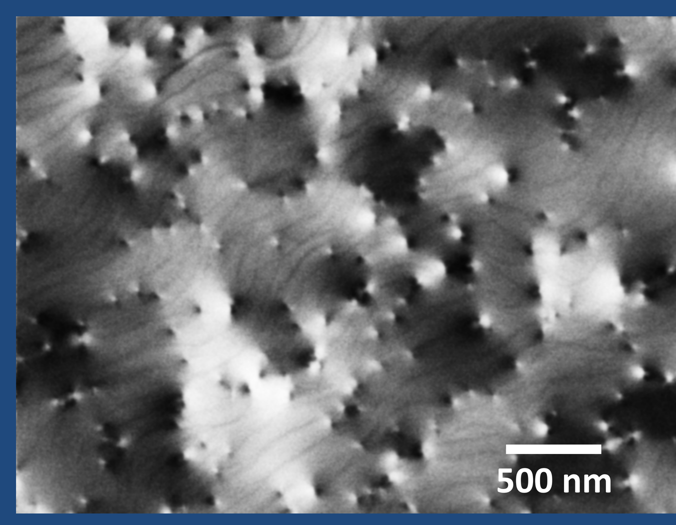
- Sample is oriented to at or close to the Bragg angle for a particular crystal plane (s).
- At the Bragg angle, θ_B, Type I & II Bloch waves have the same intensity.
- θ_B at a dislocation will be different to that of the surrounding lattice due to strain, this modulates the intensity of the backscattered electrons.
- Dislocations appear as spots with black-white contrast

References

[1] Umesh K. Mishra, Proceedings of the IEEE, **90**, 1022 (2002)
[2] Peter J. Parbrook *et al.*, Phys. Stat. Sol. (C), **0**, 2055 (2003)
[3] Junji Kotani *et al.*, Phys. Stat. Sol. (C), **10**, 808 (2013)
[4] AlN nucleation layers grown by Kyma Technologies, http://www.kymatech.com

Electron Channelling Contrast Imaging (ECCI) (cont)

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



Identifying dislocation types

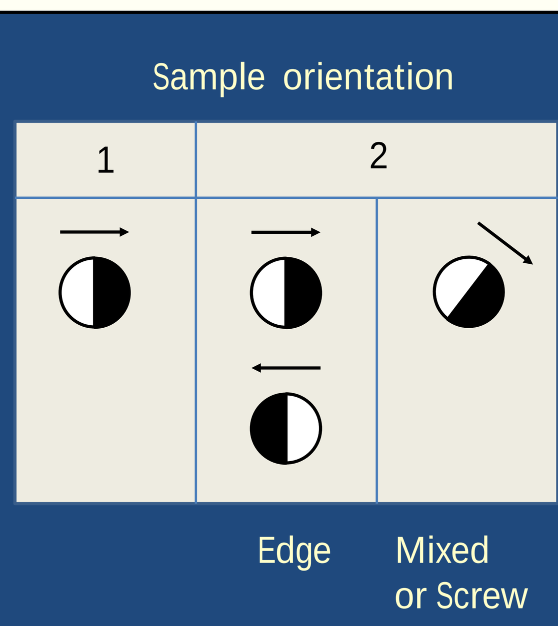
3 types of threading dislocation Edge, Screw, Mixed

Dislocation types can be identified by changing the diffraction conditions

Rotating and/or tilting the sample changes the diffraction conditions

The black-white contrast direction for edge type dislocations either stays the same or flip .on changing diffraction conditions

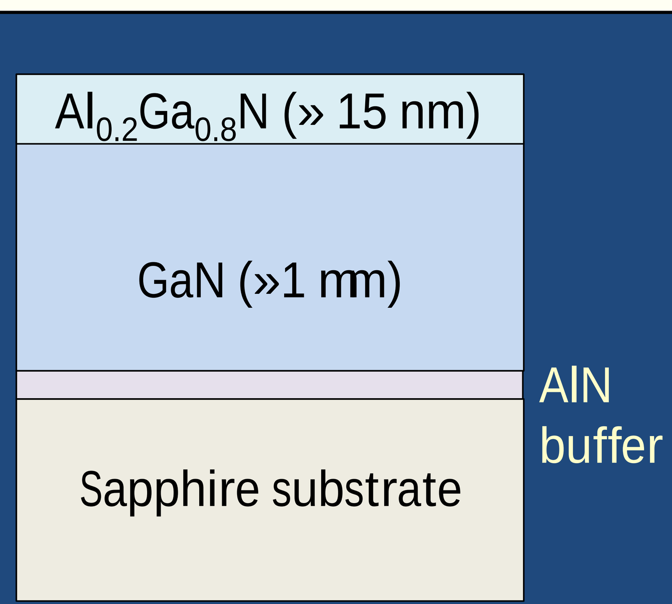
The black-white contrast direction for mixed/screw type dislocations changes on changing of diffraction conditions



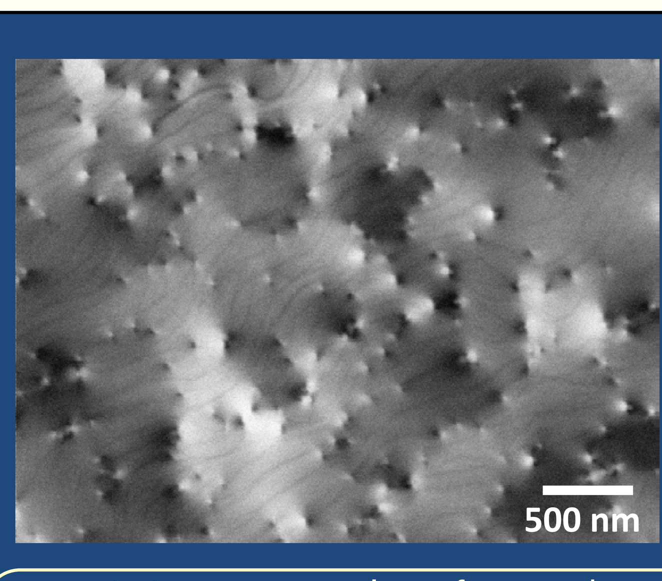
Sample Structure and growth details

$Al_{0.2}Ga_{0.8}N$(»15 nm)/GaN(»1 mm) HEMT structures were

- grown by low-pressure MOVPE
- grown on sapphire substrates with an AlN nucleation layer
- **cooled down under either H_2 carrier gas or N_2 carrier gas**



ECCI Results

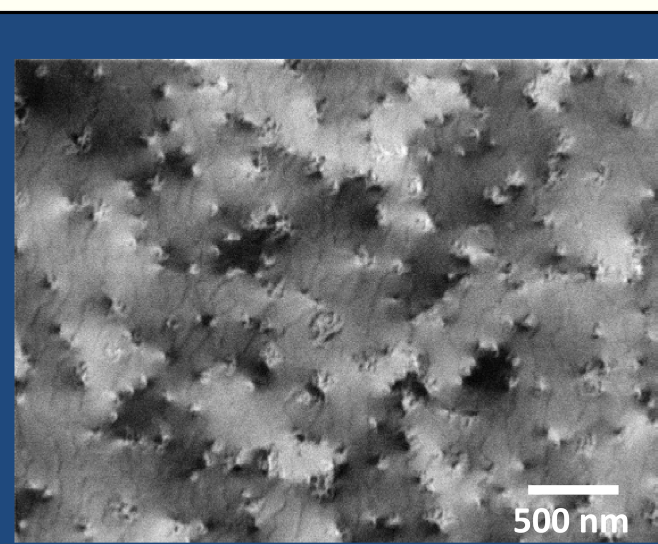


N_2 cooled – no nanoscale surface cracks

Dislocation density 2 × 10^{9} cm^{-2}

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



H_2 cooled – nanoscale surface cracks

Nanoscale surface crack density 3 × 10^{9} cm^{-2}

Sub-grains revealed by changes in grey scale. Nanoscale surface cracks located on sub-grain boundaries – so are probably due to dislocations

Electrical Results

Cooling Carrier gas	300K R_{sh} (Ohm/square)	300K Mobility (cm²/V.s)	300K n_{sh} (cm^{-2})
H_2	983	985	6.40 × 10^{12}
N_2	904	996	6.93 × 10^{12}

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 barrier 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 AlGaN/GaN HEMTs.