Mapping of the Strain and Distribution of Dislocations in InAlN based HEMTs using Backscatter Electron Diffraction and Electron Channelling Contrast Imaging

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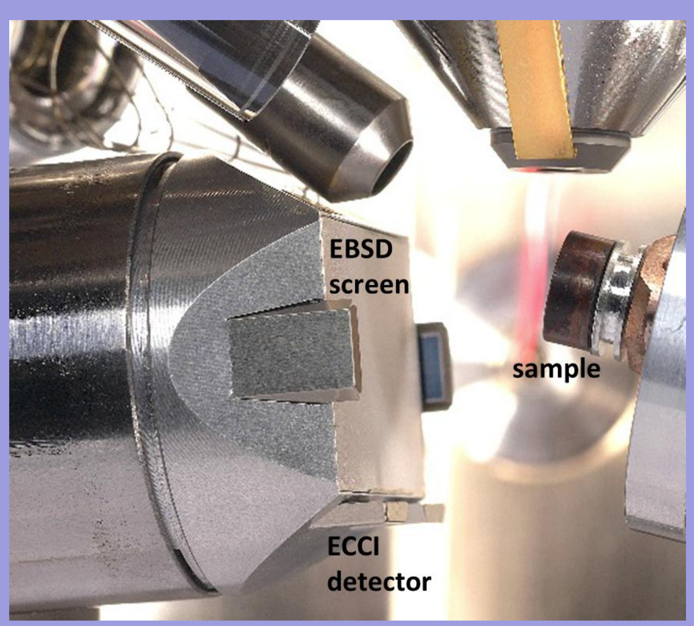
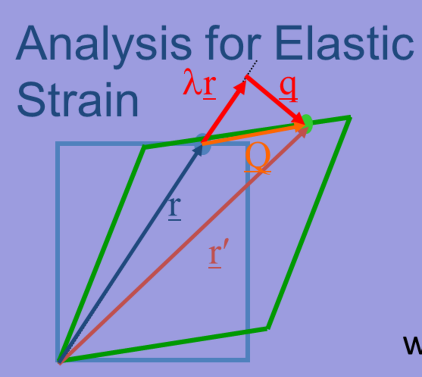
Motivation

- The two-dimensional electron gas (2-DEG) formed at the interface due to the presence of piezoelectric and polar electric fields in High Electron Mobility Transistors (HEMTs) may be critically influenced by the structural quality; i.e. the distribution of strain and the presence of defects.
- Developing the capability to analyse dislocations, determine their densities rapidly, non-destructively and to extract quantitative information on crystal orientation and strain, will represent a significant step forward for the development of high quality electronic and optoelectronic devices.
- Using electron channelling contrast imaging (ECCI), coupled with the acquisition of electron backscattered diffraction (EBSD) patterns in a scanning electron microscope (SEM), can provide such a capability.
- The objective of this work is to combine the two techniques of ECCI and EBSD to provide both qualitative and quantitative information on the structural properties of InAlN/AlN/GaN heterostructures grown on two different substrates, namely SiC and sapphire by metal organic vapour phase epitaxy (MOVPE).

Experimental details



Conventional geometry for EBSD and ECCI



deformation maps $\underline{r}$ to $\underline{r}'$

$\underline{r}' = \mathbf{A}\,\underline{r}$

displacement $\underline{Q}$ is given by

$\underline{Q} = \underline{r}' - \underline{r} = (\mathbf{A}-\mathbf{I})\,\underline{r}$

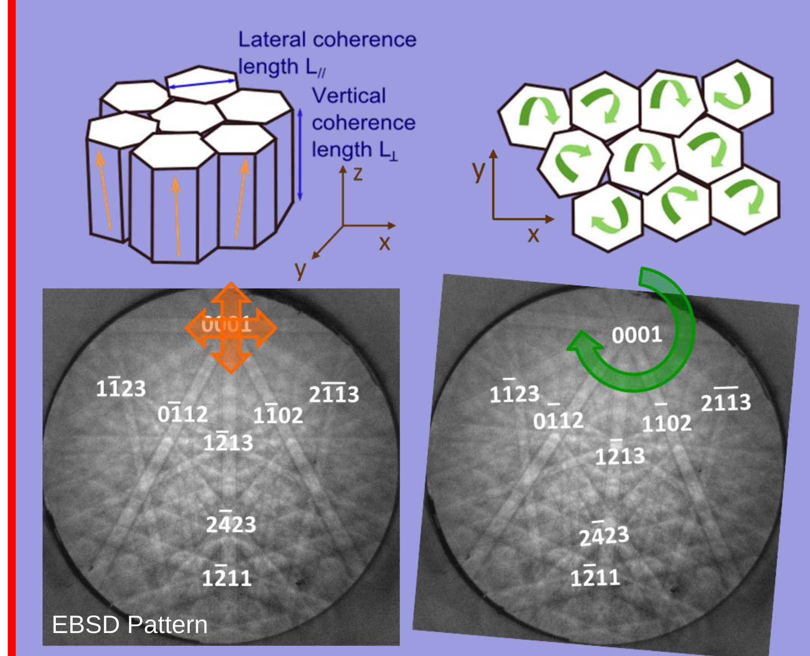
with EBSD can measure components of $\underline{Q}$ that are perpendicular to $\underline{r}$

$\underline{q} = \underline{Q} - \lambda\underline{r} = \{\mathbf{A} - (\lambda+1)\,\mathbf{I}\}\,\underline{r}$

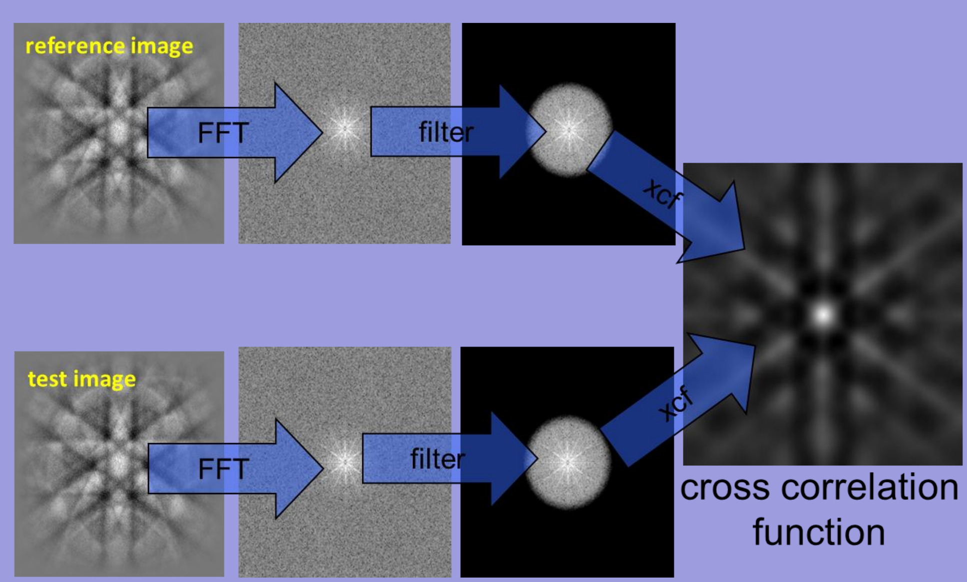
$$\mathbf{A}-\mathbf{I} = \begin{pmatrix} \frac{\partial u}{\partial x} & \frac{\partial u}{\partial y} & \frac{\partial u}{\partial z} \\ \frac{\partial v}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial z} \\ \frac{\partial w}{\partial x} & \frac{\partial w}{\partial y} & \frac{\partial w}{\partial z} \end{pmatrix}$$

measurement of $\underline{q}$ for 4 different directions, $\underline{r}$, allows 8 of the 9 degrees of freedom in **A** to be found

- A distortion in a crystal will produce a distortion of the EBSD pattern (see below).
- By measuring this distortion, information on tilt, twist and strain can be calculated.
- The introduction of cross-correlation based analysis of EBSD patterns has seen a step change in the angular resolution to ≈10^{-4} rads [1].
- This is sufficient to enable analysis of the misorientations and local elastic strain fields that are typical in nitride semiconductor materials.
- Recent advancement in ECCI for revealing and identifying threading dislocations (TDs) [2] and imaging stacking faults [3] non-destructively makes ECCI ideal for characterising extended defects in nitride semiconductors.



Measuring tilt and twist with EBSD. Tilt or twist In the crystal will show an change in the EBSD pattern.



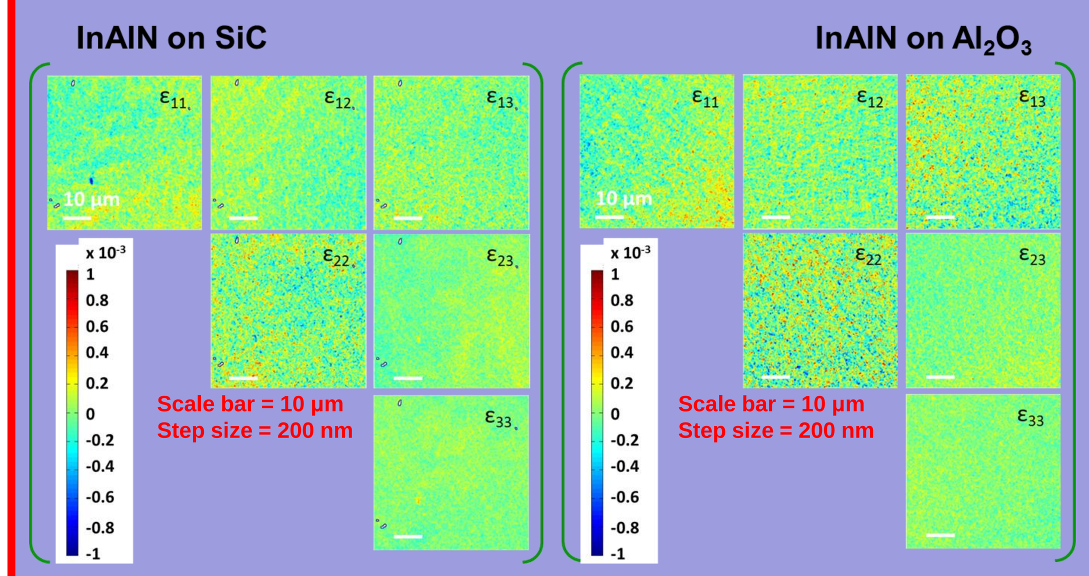
Measuring strain with EBSD using cross-correlation analysis.

$In_{0.21}Al_{0.79}N$ (10nm)	$In_{0.18}Al_{0.82}N$ (10nm)
AlN (4 nm)	AlN (4 nm)
GaN buffer (1.7 µm)	GaN buffer (3 µm)
AlGaN nucleation layer	GaN nucleation layer
SiC (semi insulating)	Al_2O_3
Compressive strain	Tensile strain

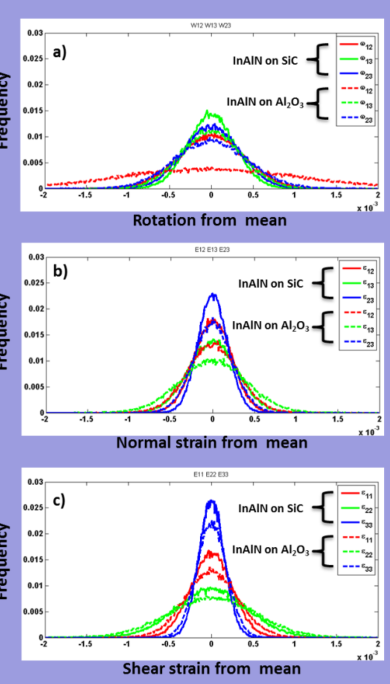
- HEMT structures grown by low pressure-MOVPE using an AIXTRON AIX200RF horizontal reactor on a 2" inch, 4H-SiC and sapphire wafers.
- Electron mobility of 1240 $cm^2V^{-1}s^{-1}$ and 1050 $cm^2V^{-1}s^{-1}$ is achieved for the HEMTs grown on SiC and sapphire substrates respectively [4].
- EBSD and ECCI were aquired at electron beam energies of 20 keV and 30 keV respectively.

Results and discussion

EBSD



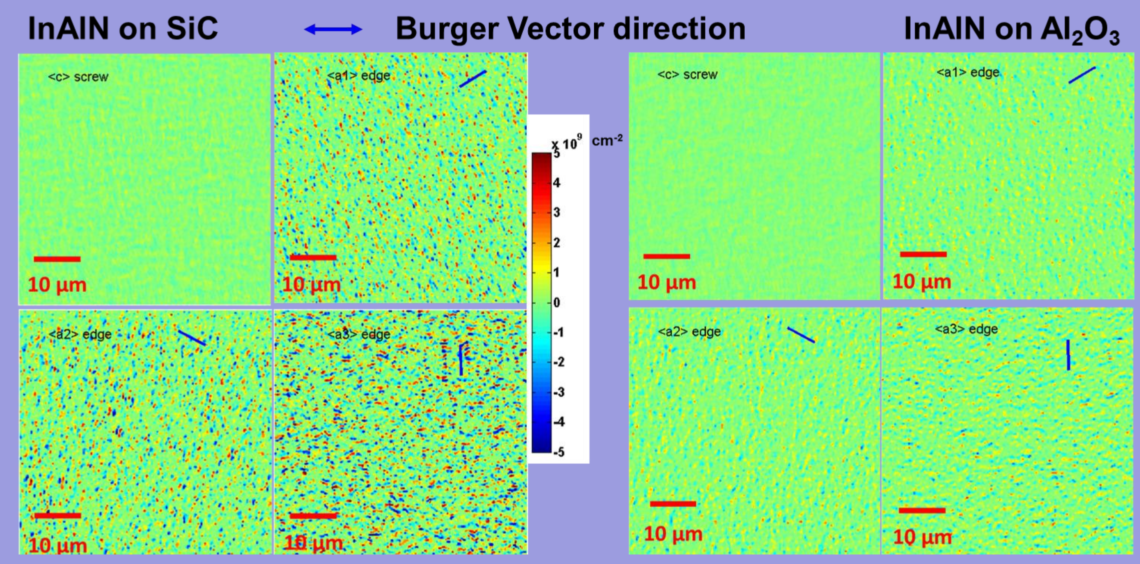
Normal and shear strain maps of the HEMT structures



Tilt (ω_{13}& ω_{23})
Twist (ω_{12})
Normal strains (e_{11}, e_{22} and e_{33})
Shear strains (e_{12}, e_{13} and e_{23})

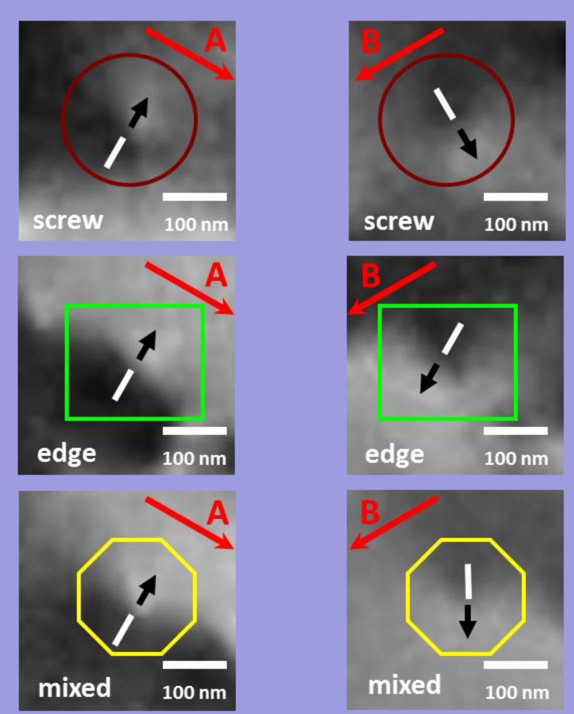
e_{11} - along [10-10]
e_{22} - along [1-120]
e_{33} - along [0001]

Screw = <0001> Edge = 1/3 <11-20>

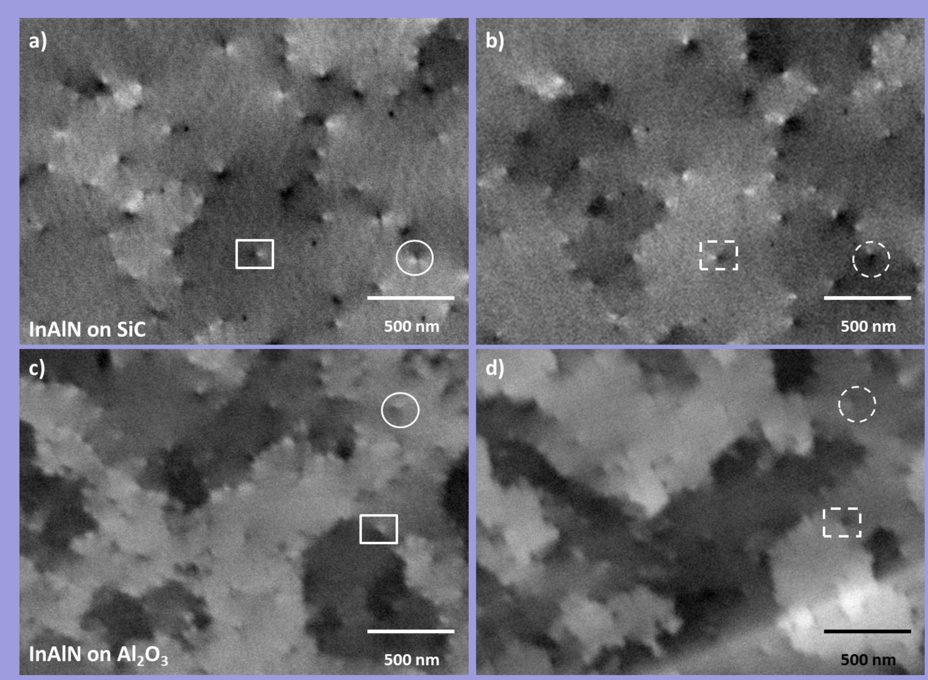


Distribution of geometrically necessary threading dislocations derived from EBSD

ECCI



Threading dislocations are identified from the change in contrast when channelling is switched from plane A to plane B [2]



ECCI taken from the same part of the sample with two different channelling conditions to estimate the TDs types for the HEMT structures grown on SiC (a & b) and on Sapphire (c & d). The rectangle and the circles highlight edge and screw/mixed dislocations respectively.

Summary

- For the HEMT structures, tilt, twist and elastic strain were measured and histograms were constructed of the rotations (ω_{12} twist mosaic) and (ω_{13} and ω_{23} tilt mosaics).
- Similar histograms for each of the strain variations in the surface plane were also constructed.
- The strain variations were smaller when compared to rotations.
- The width of the twist mosaic was found to be larger than the tilt mosaic.
- ECCI reveals that InAlN grown on SiC and sapphire has a total TD density of 1.4 × 10^9 cm^{-2} and 2.9 × 10^9 cm^{-2} respectively.
- Both samples have a similar ratio of edge to screw type TDs (edge ≈ 65% and screw type ≈ 35%).
- EBSD and ECCI results indicates that edge type TDs are present in greater density than screw type for both the samples.
- HEMT grown on sapphire has larger dislocation density (≈ twice) when compared to the HEMT grown on SiC, this might explain the lower electron mobility for the HEMT grown on sapphire.

Conclusions

- Combination of EBSD and ECCI techniques provides both qualitative and quantitative information on the structural properties of nitrides based electronic devices.
- Being SEM based techniques it is possible to simultaneously acquire multiple signals correlating compositional, optical, electrical & structural characteristics from the same part of the sample.

References

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