Carrier localisation, efficiency droop, cubic GaN and the green gap

CAMBRIDGE CENTRE FOR GALLIUM NITRIDE

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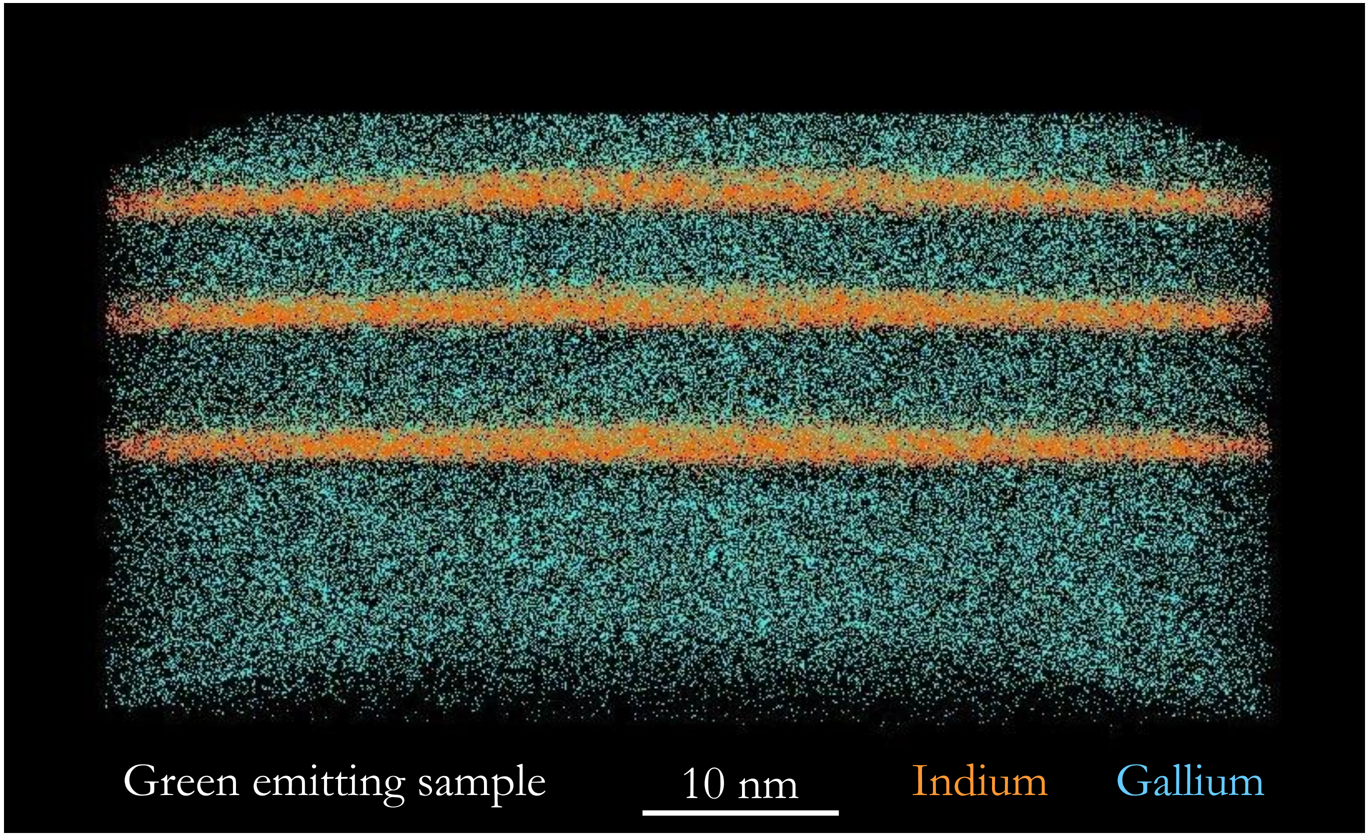
- EPSRC
- Innovate UK
- Plessey
- Anvil Semiconductors

Why is GaN a lucky semiconductor?

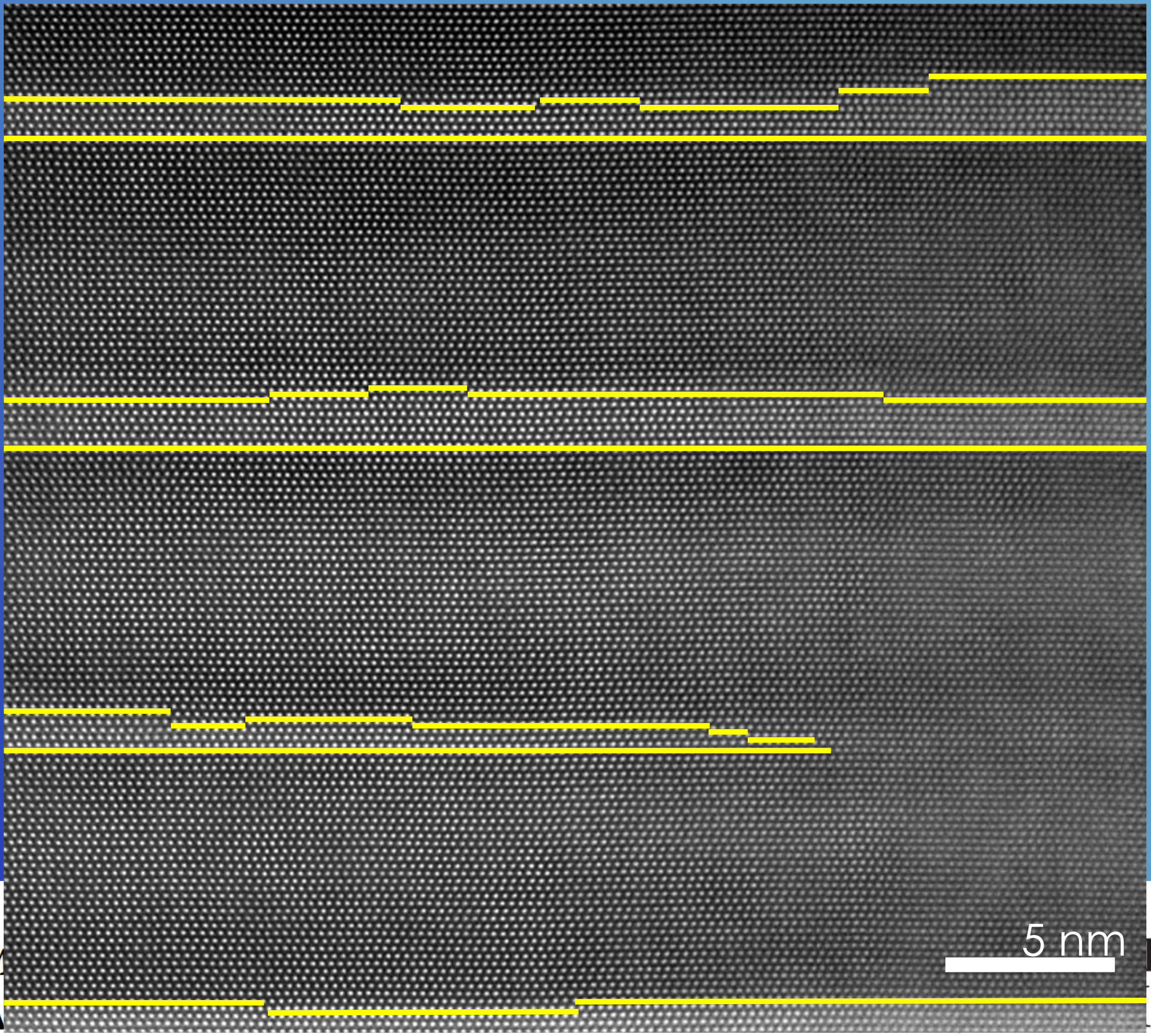
- High density of threading dislocations (~10^9 cm^{-2})
- Threading dislocations are non-radiative recombination centres (CL)
- For efficient light emission in other semiconductors, dislocation density should be less than ~10^3 cm^{-2}
- Why is GaN lucky? Carriers are localised in InGaN QWs (e.g. the S-curve). This prevent the carriers from reaching the dislocations.
- What is causing the carrier localisation?

APT imaging of polar InGaN QWs



InGaN is a random alloy. **There are no In-rich clusters in polar blue and green QWs**

FEI Titan image of InGaN/GaN QWs



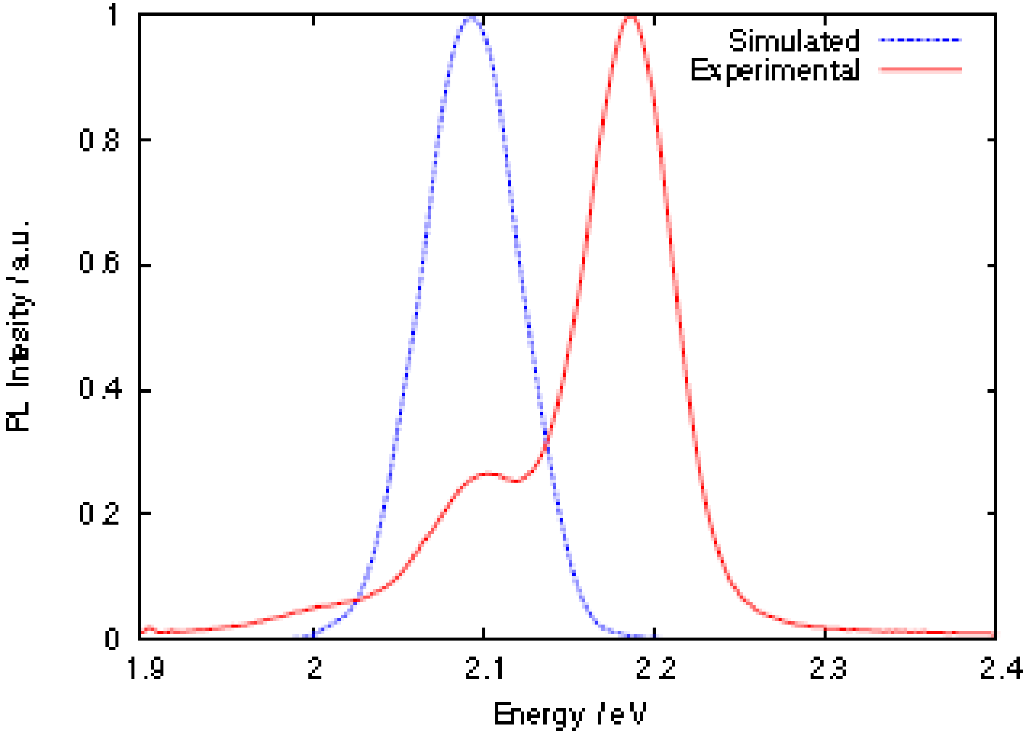
Modelling

- ***APT/TEM data used as an input for theoretical model to solve the Schrödinger equation***
  - InGaN is a random alloy
  - QW has thickness fluctuations (monolayer, bilayer)
- **Original theory by Duncan Watson-Parris et al (Manchester, Cambridge)**
- **Later theory by Stefan Schulz (Tyndall Institute, Cambridge)**

Key points from modelling InGaN QWs

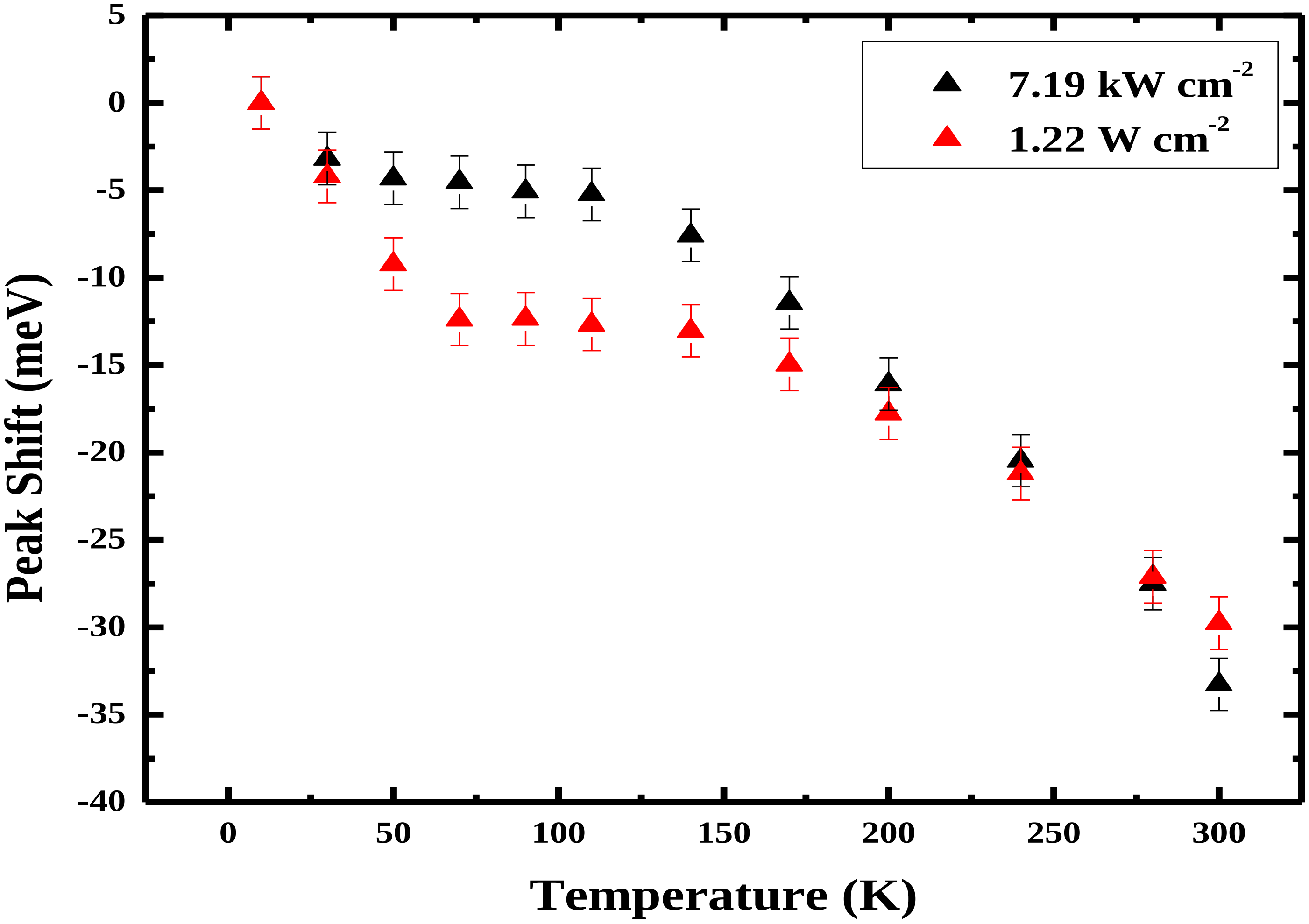
- Random In fluctuations localise the holes (For In average content 0.25: localisation energy 5-190 meV, localisation length 1-2 nm)
- QW thickness fluctuations localise the electrons (localisation energy 1-35 meV, localisation length about 5 nm)
- Note: kT at 300K = 25 meV. Most e and h localised at 300K.
- Coulomb interaction much less. Hence e and h are independent carriers in polar InGaN QWs
- Think of an InGaN QW as containing many nm-size InGaN quantum dots of varying In content hence varying potential depth
- Carrier diffusion to defects is prevented by carrier localisation: a natural QW nanostructure

Simulation of Low Temp PL spectrum $In_{0.25}Ga_{0.75}N/GaN$



Variation in hole localisation mainly responsible for line width

‘S-shape’ Temperature Dependence of Peak Position



S-curve at different carrier densities

- Intensity and wavelength measured at different temperatures as a function of the laser power
- At high power the S curve disappears.
  - Corresponds to the saturation of localised states
- The onset of efficiency droop occurs at the *same* excitation power density as the onset of carrier delocalisation

Carrier localisation and efficiency droop

- Localised carriers are in local potential minima
- At low current density, this localisation prevents carriers from diffusing to dislocations, leading to high efficiency of light emission
- At high current density, carriers fill the local potential minima, the localised states become saturated, additional carriers are not localised, hence they can diffuse to defects, be more available to Auger, and the efficiency drops

What effect(s) correlates with the onset of efficiency droop?

- Does a change in the localisation of carriers?
  - ***We say YES***
- Does the onset of Auger-dominated recombination?

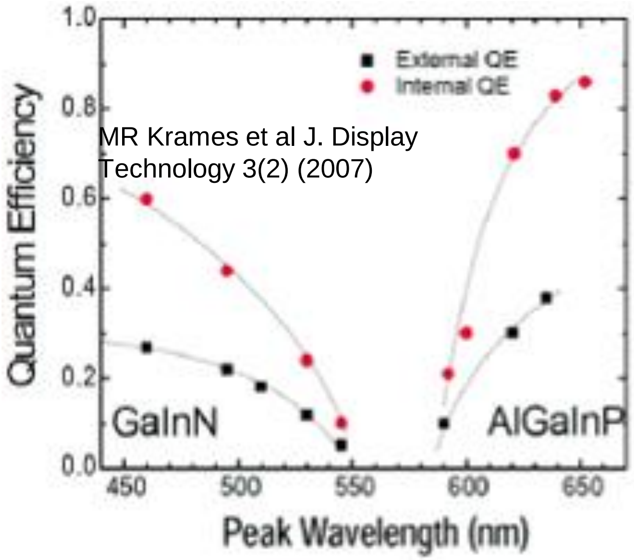
  -- ***UCSB says YES***
- If both are correct, then the change in the localisation of carriers may enable the onset of increased Auger recombination

Conclusions

- At onset of droop there is simultaneous change in the S-shape temperature dependence of the PL due to the saturation of localised states
- Excess carriers injected are free to diffuse to defects and may also enable the onset of Auger recombination
- Suggests that the saturation of localised states initiates droop by an Auger mechanism and possibly also by a defect mechanism

Why is there a green gap problem?

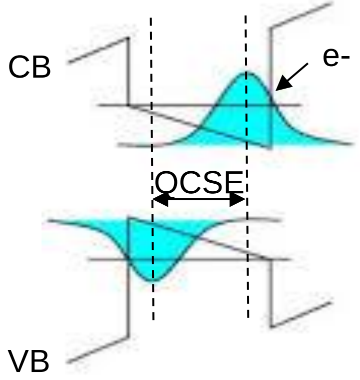
- **Piezoelectric field across InGaN QW increases as In content increases.**
    - **Hence e and h separation increases**
    - **Hence light emission decreases**



MR Krames et al J. Display Technology 3(2) (2007)

- **Lower growth temperature required to incorporate more Indium in MQW.**
    - **Hence increased number of point defects**

InGaN Q-well Band structure

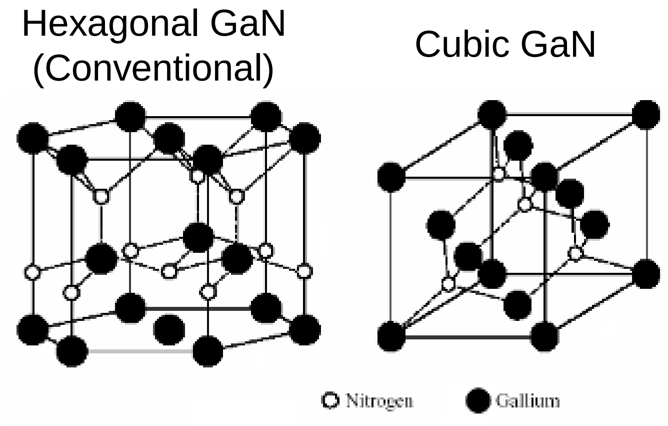


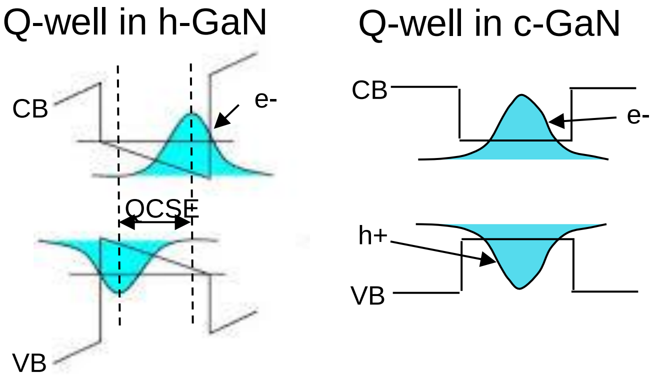
Solution to the green gap problem?

- Eliminate the piezoelectric field across the QW
- Grow the InGaN QW at higher temperature

Cubic GaN

Property	h-GaN	c-GaN
Band Gap	3.4eV	3.2eV
Internal Electric Field	Yes	No
Thermodynamically stable at RT	Yes	No





- **Reduced band gap gives longer emission for the same QW In content**
  - **Higher QW growth temperature**

- **Removal of Internal electric fields should increase e-h wavefunction overlap**

- **Innovate UK funded project to develop cubic-GaN LEDs**
  - **Collaboration with Anvil and Plessey**

Cambridge Centre for Gallium Nitride

University of Cambridge

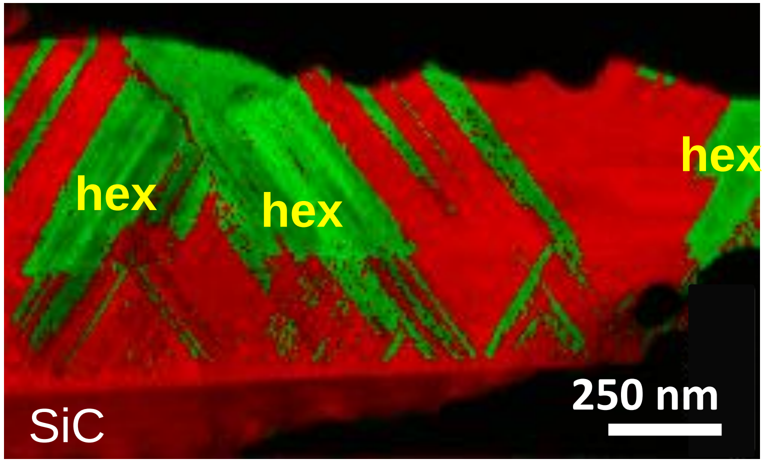
Substrate for Cubic GaN Growth

- 3C-SiC on (001) Si
  - $a_{3C\text{-}SiC}$ = 0.436nm
  - $a_{cubic\text{-}GaN}$ =0.452nm
  - Lattice mismatch = 3.7%
- High quality 3C-SiC on Si is being developed by Anvil Semiconductors for SiC power electronics applications
  - Grid pattern used for stress relief
- Cubic GaN growth on 150mm wafers recently demonstrated
  - Clear route to commercialisation

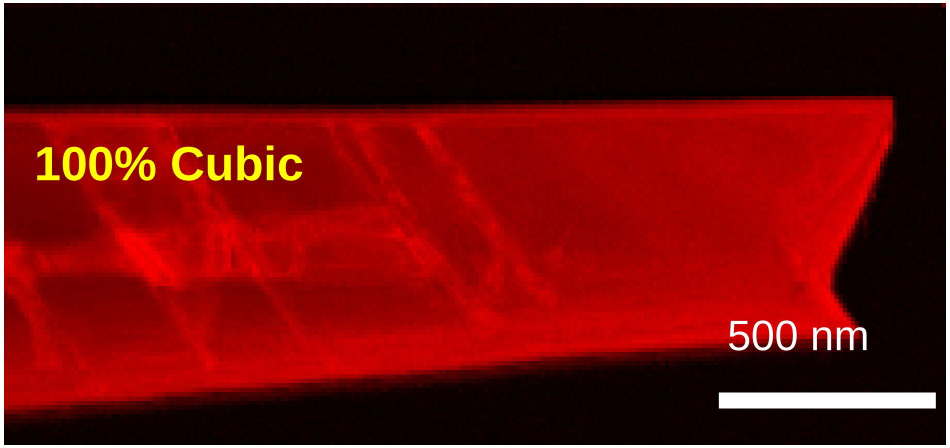
150mm diameter 3C-SiC on (001)Si

Cubic-GaN Material Quality

Nano diffraction mapping (5nm resolution) of crystal phase

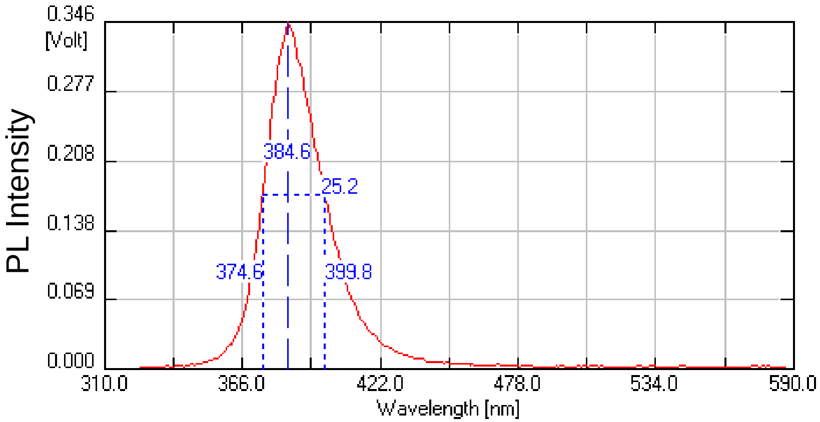


Early Growth



Optimised Growth

PL at Cubic GaN Band edge

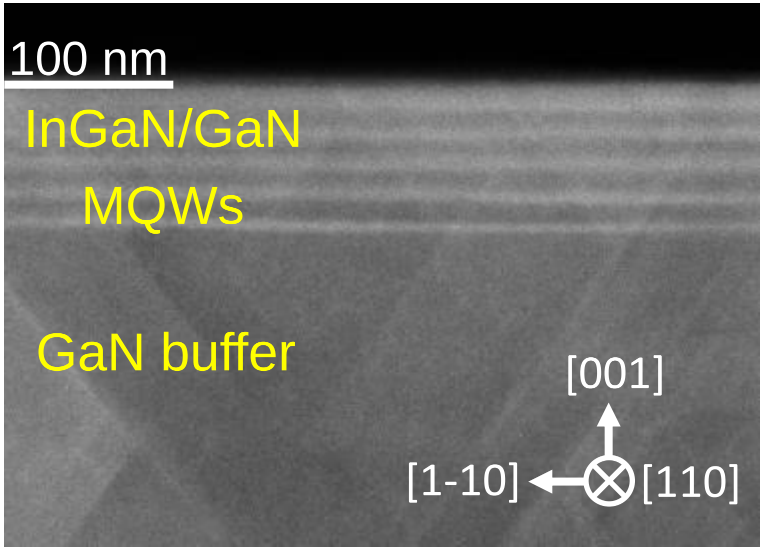


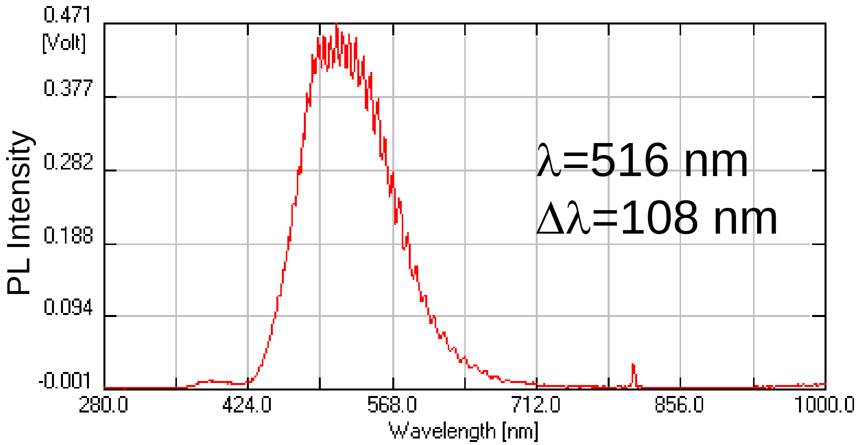
- **Early growth experiments show hexagonal phase inclusions (green)**
- **Optimum growth conditions give 100% cubic phase (red)**
- **PL shows clear cubic emission at 385nm (3.22eV)**

Cubic-InGaN MQWs

- Initial trials of InGaN Q-wells show strong green emission

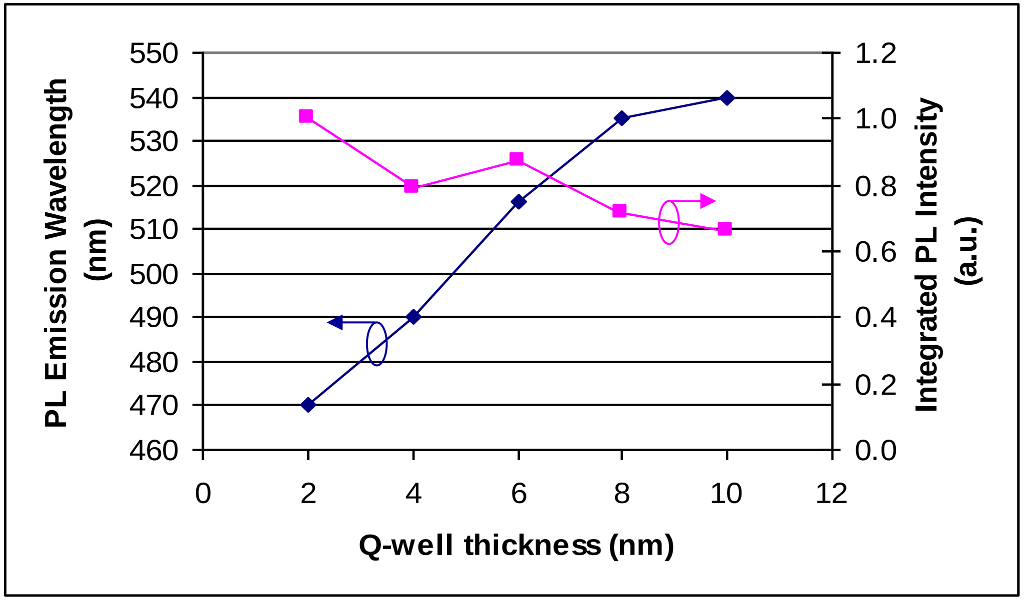
- c-QW growth temperature similar to that for h-QW emitting at 460nm
  - Reduced point defects?
- Only 10% In used in cubic, cf 25% In for hexagonal
- Strong PL emission despite stacking faults (SF) seen in TEM
  - SF density ≈10^4 cm^{-1} at the surface of this layer
- First steps to growing Cubic GaN-on-Si LEDs: looks promising!





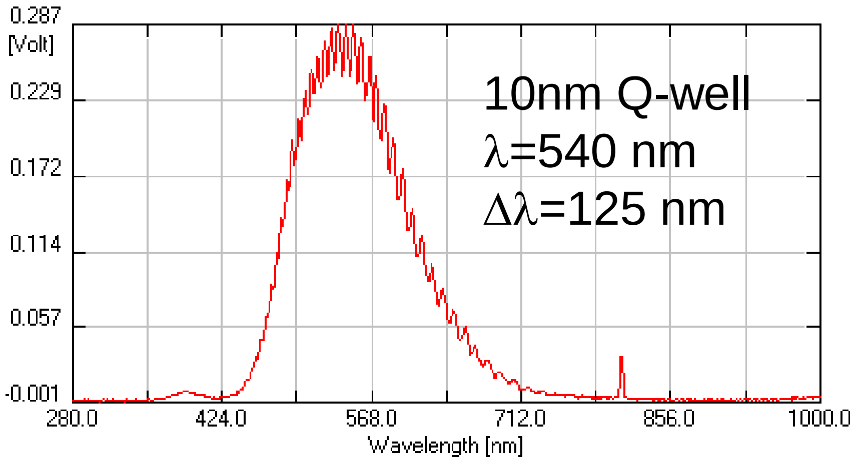
Cubic InGaN – Effect of QW Thickness

- **Increasing the QW thickness shows a clear shift of emission wavelength**
  - **Reduced quantum upshift of confined states in QW**
  - **Indium content =10±1%**



- **PL emission intensity reduction is relatively small with increasing wavelength up to 540nm**

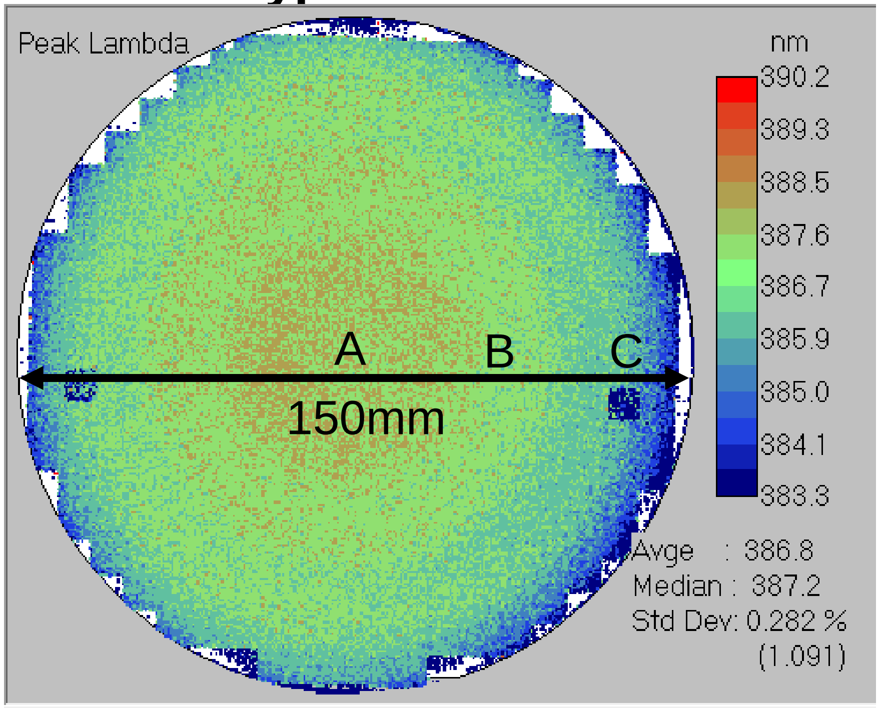
- **Reduced droop in thicker QWs?**

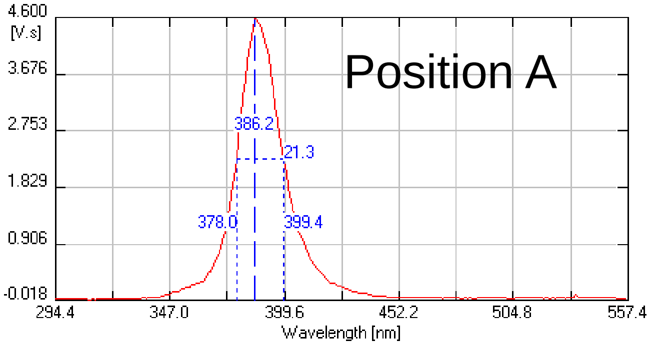


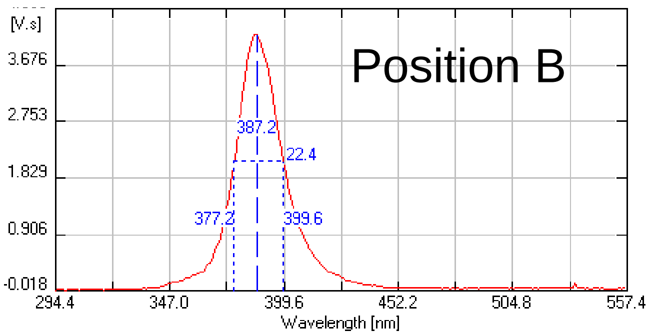
10nm Q-well
λ=540 nm
Δλ=125 nm

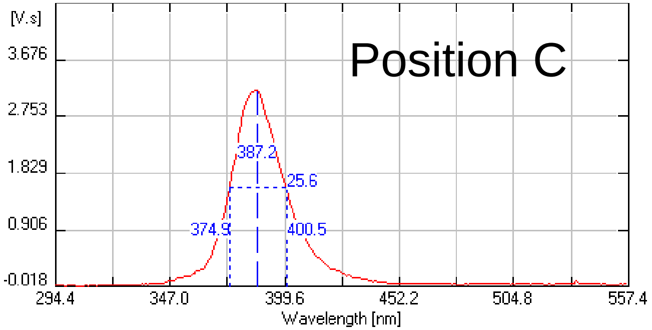
GaN Growth on 150mm 3C-SiC/Si

PL Map of Near Band Edge Emission from n-type c-GaN









- **NBE emission at 385 -389nm cubic across most of the wafer area**
- **No regions of PL emission at 365nm indicating no large h-GaN Inclusions**

Summary of cubic GaN

- MOCVD growth of single phase cubic GaN films
- Strong PL MWQ emission up to 540nm with c-QWs grown at similar temperatures to h-MQWs emitting at 460nm
- Growth on 150mm substrates
- Compatibility with commercial LED processing line
    - Wafer bow <50um for 150mm wafer

- First steps towards demonstrating a viable cubic GaN LED technology

USA-UK collaboration on SSL?

- UK coming out of Europe (Brexit)
- Donald Trump looking for new trade deal with UK
- Donald Trump/Theresa May hand-in-hand
- Should we form a DOE/BEIS partnership on SSL?
- If of interest to the DOE, I can approach BEIS in the UK about this