Materials challenges for devices based on single, self-assembled InGaN quantum dots

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1. Introduction

- Building on our studies of the properties of InGaN quantum dots (QDs) grown by a modified droplet epitaxy technique [1,2], we are considering potential designs for GaN-based optically or electrically-pumped single-photon sources.
- The InGaN QDs emit in the blue or green spectral region, providing a good match to commercially-available, highly sensitive, ultra-fast avalanche photodiodes.
- One device concept (Fig. 1.1) involves the incorporation of a layer of QDs with a low spatial density into a resonant-cavity LED.
- Luminescence could be limited to that from a single dot by using a metallic mask or by etching mesa structures.
- Realisation of such a concept poses a number of challenges in crystal growth, two of which are considered here:

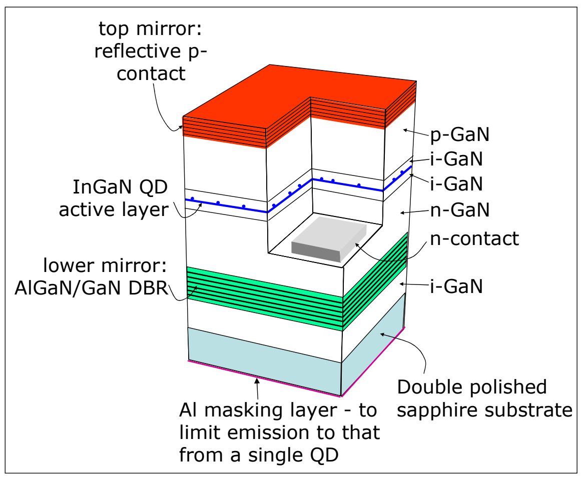


Figure 1.1: *Schematic of a conceptual single photon source based on InGaN quantum dots. (Not to scale.)*

- (A) the growth of the QD layer on an underlying distributed Bragg reflector (DBR).
  - Typical nitride based DBRs are based on alternating layers of AlGaN and GaN.
  - The strain between these layers results in surface roughening and an increasing density of defects, which may effect subsequent QD growth.
- (B) The growth of a p-type GaN cap on top of the QD layer.
  - Under typical growth conditions, the p-type dopant (Mg) forms an electrically inactive complex with hydrogen.
  - Acceptor activation then requires an extended high temperature anneal.
  - This annealing process may damage the underlying QD layer.

[1] RA Oliver *et al.* Appl. Phys. Lett. **83,** 755 (2003),
[2] JW Robinson *et al.* Appl. Phys. Lett. **86**, 213103 (2005)

2. Experimental

- All samples described in this poster were grown by metal-organic vapour phase epitaxy (MOVPE) in the Thomas Swan 6 x 2", Close-couple Showerhead reactor at the Cambridge GaN centre.
- Tri-methyl indium, tri-methyl gallium, tri-methyl aluminium, ammonia, silane, and bis(cyclopentadienyl)magnesium are used as precursors with N_2 as a carrier gas.
- The quantum dot growth methodology had been described elsewhere [1]. A postulated growth mechanism is illustrated in Figure 2.1.
- Surface morphologies were studied using a Veeco Dimension 3100 AFM in TappingMode™.
- Room temperature photo-luminescence (PL) was performed using a HeCd laser operating at 325 nm.
- Low temperature, spatially-resolved micro-PL measurements were made using 1 ps pulses from a tunable Ti:sapphire laser. Two-photon excitation was used.
- A 36× achromatic microscope objective lens was used to focus the laser to a spot of ~2 μm, reducing the number of QDs excited, and allowing the resolution of single QD peaks.

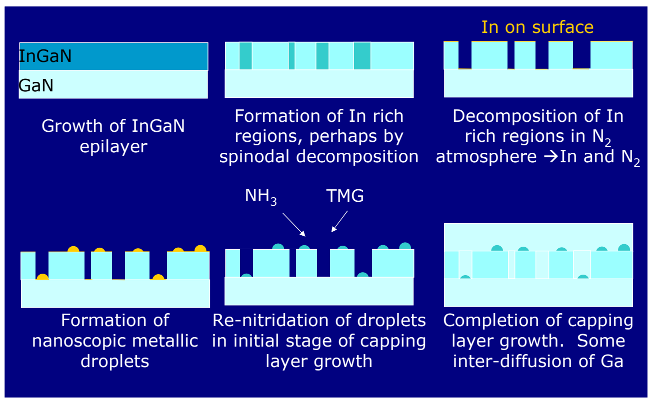


Figure 2.1: *Postulated QD growth mechanism in InGaN/GaN system*

- The same microscope objective lens was used to collect the PL.
- Time-integrated PL spectra were recorded by using a cooled CCD mounted on a 0.3 m monochromator, with 600 or 1200 grooves/mm gratings.
- An automated mirror allowed the PL to be redirected to another apparatus at the exit of the monochromator in order to perform time-resolved measurements.
- A time-resolution of ~150 ps was achieved using time-correlated single photon counting system based on a fast photomultiplier.
- The measurements were made at 4.2 K using a continuous-flow cryostat.

3. Results A: Quantum dot growth on a distributed Bragg reflector

Structures studied

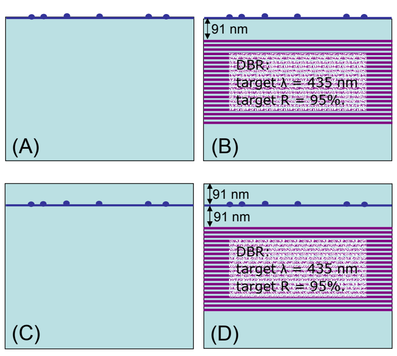


Figure 3.1: *Schematic diagrams of structures studied (not to scale).*
(A) InGaN QD epilayer on standard GaN substrate.
(B) InGaN QD epilayer with underlying 20 period AlN/GaN DBR.
(C) InGaN QD layer capped with 91 nm GaN.
(D) InGaN QD layer grown on underlying 20 period AlN/GaN DBR and capped with 91 nm GaN.
Additionally the surfaces of the samples at the stage just prior to QD growth were examined.

InGaN QD epilayers

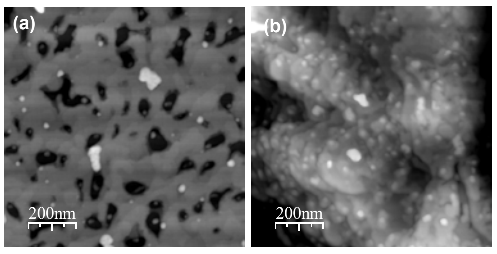


Figure 3.3: *AFM images of (a) sample A: InGaN QD epilayer grown on a standard GaN substrate (h = 11.75 nm) and (b) sample B: InGaN QD epilayer grown on underlying AlN/GaN DBR (h = 21.49 nm).*

Although nanostructures are observed following epilayer growth on either surface, both the overall morphology and the number density of nanostructures is very different.

Room temperature PL

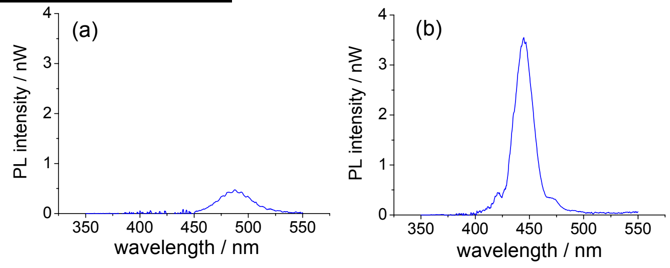
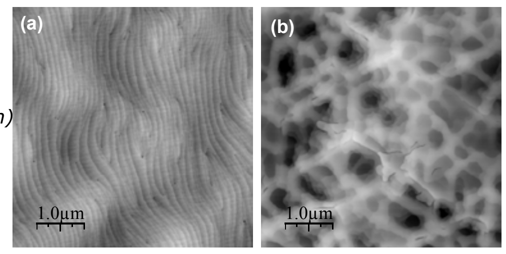


Figure 3.5: *Room temperature PL spectra for (a) sample C: capped InGaN QD layer on standard GaN substrate and (b) sample D: capped InGaN QD layer grown on underlying AlN/GaN DBR. Note blue-shift and increase in intensity for sample with DBR.*

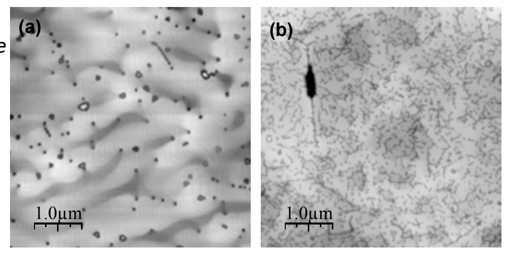
"Substrate" surfaces

Figure 3.2: *AFM images of (a) a standard GaN substrate (image height, h = 3.16 nm) and (b) the surface of a DBR sample at the stage just prior to QD growth (h = 27.65 nm).*



Capped QDs

Figure 3.4: *AFM images of (a) sample C: InGaN QD layer capped with 91 nm GaN (h = 10.48 nm) and (b) sample D: capped InGaN QD layer grown on underlying AlN/GaN DBR (h = 167.19 nm).*



Low temperature micro-PL

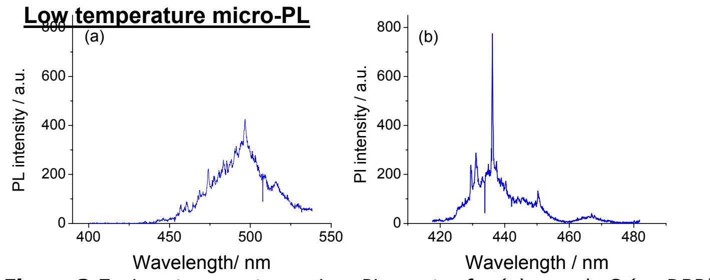


Figure 3.5: *Low temperature micro-PL spectra for (a) sample C (no DBR) and (b) sample D (with DBR). Note enhanced QD signal–to–background ratio for sample with DBR.*

Although enhanced single QD PL may be observed for the capped sample with the DBR, the high roughness of its top surface prevents the successful growth of an upper reflector. More development of the DBR structure is required.

4. Results B: Quantum dot growth with a p-type cap layer

Structures studied

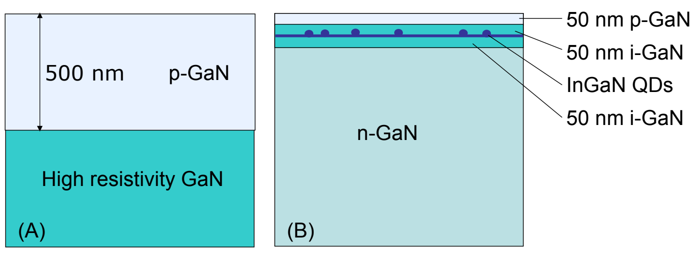


Figure 4.1: *Schematic diagrams of structures studied (not to scale).*
(A) Control p-type GaN epilayer. Hall measurements give acceptor concentration of ~ 1 × 10^{17} cm^{-3}.
(B) QD p-i-n diode structure. The n-type GaN substrate has a donor concentration of ca. 2 × 10^{18} cm^{-3}. The QD layer is at the centre of a 100 nm thick unintentionally doped region, and is capped with 50 nm p-type GaN, grown under similar conditions to the p-GaN in sample (A).

p-type GaN cap: Growth details

- Growth at 1000 °C for 104 s.
- Molar gas flows: Cp_2Mg – 1.6 μmol/min, TMG – 255 μmol/min, NH_3 – 446 mmol/min.
- Cool to 780 °C and stabilise.
- Anneal for 1200 s in 20 slm N_2.

We have investigated the impact of this capping procedure on QD luminescence

Room temperature PL

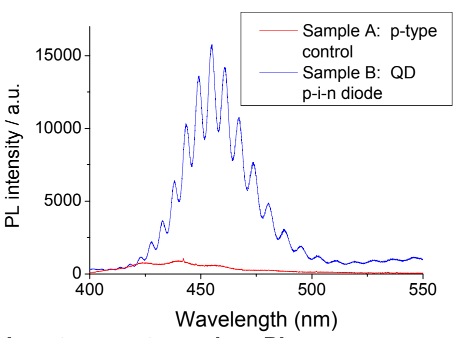


Figure 4.2: *Comparison of RT PL from the control p-type layer (Sample A) which exhibits weak blue luminescence and QD p-i-n diode (Sample B), which exhibits much brighter luminescence at a somewhat longer wavelength, suggesting that the PL originates in the QD layer not the p-type cap.*

Low temperature micro-PL

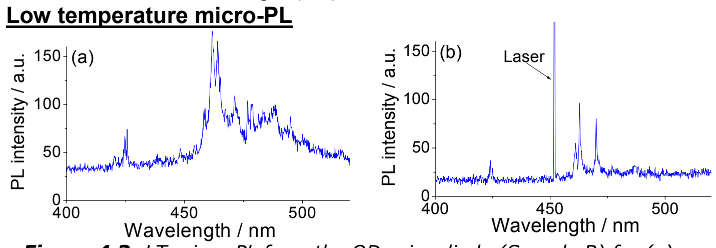


Figure 4.3: *LT micro-PL from the QD p-i-n diode (Sample B) for (a) Excitation wavelength, λ= 780 nm, excitation power, P = 35 mW, (b) λ= 900 nm, P = 60 mW. Note sharp QD peaks, and suppression of background signal in (b), with longer wavelength excitation.*

Time-resolved PL

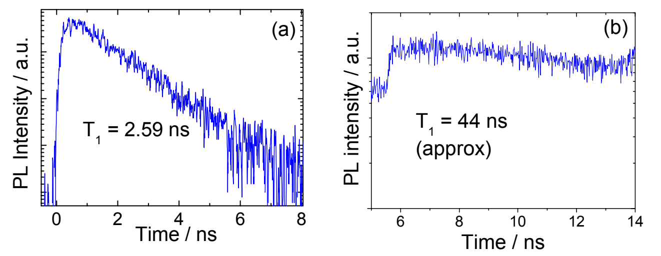


Figure 4.4: *Comparison of decay traces from a single QD in (a) a QD sample without a p-cap and (b) sample B, the QD p-i-n diode. Note the extended exciton lifetime for the QD in sample B.*

Room temperature electroluminescence

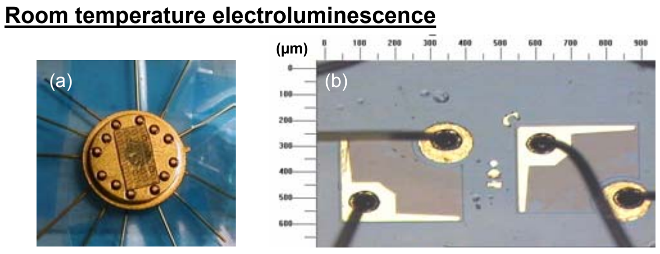


Figure 4.5: *Processed LEDs from sample B: (a) Overview. (b) Detail)*
We have observed blue electroluminescence from the QD p-i-n diode at room temperature. A forward voltage of 6.5 V gives a current of 20 mA.

We have successfully demonstrated growth of a p-cap on a QD sample, without quenching of the QD luminescence. Changes to the properties of the QDs during the anneal – perhaps due to interdiffusion of QD and matrix material – require further investigation. In later studies, we also hope to observe single QD electroluminescence at low temperature.

5. Conclusions

- We have explored two crystal growth challenges relevant to the construction of an InGaN quantum dot single photon source.
- We have successfully grown a QD layer on top of an AlN/GaN DBR and demonstrated enhanced QD luminescence.
- The top surface of the sample with the DBR is excessively rough. Further DBR development is required.
- We have successfully demonstrated that InGaN QDs can survive the growth and anneal of a p-type cap.
- The QD p-i-n diode shows blue electroluminescence at RT.

6. Acknowledgements

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