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InGaN Quantum Dots for High Efficiency Blue and Green Light Emitters

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Outline:

1. QD Motivation
2. InGaN QD fabrication
3. AFM/TEM analysis of InGaN QDs
4. Optical characterization of QDs
5. Summary/Conclusions

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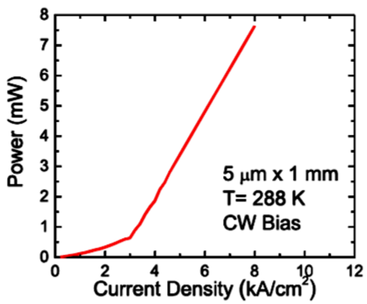
Motivation for InGaN Quantum Dot (QD) Emitters

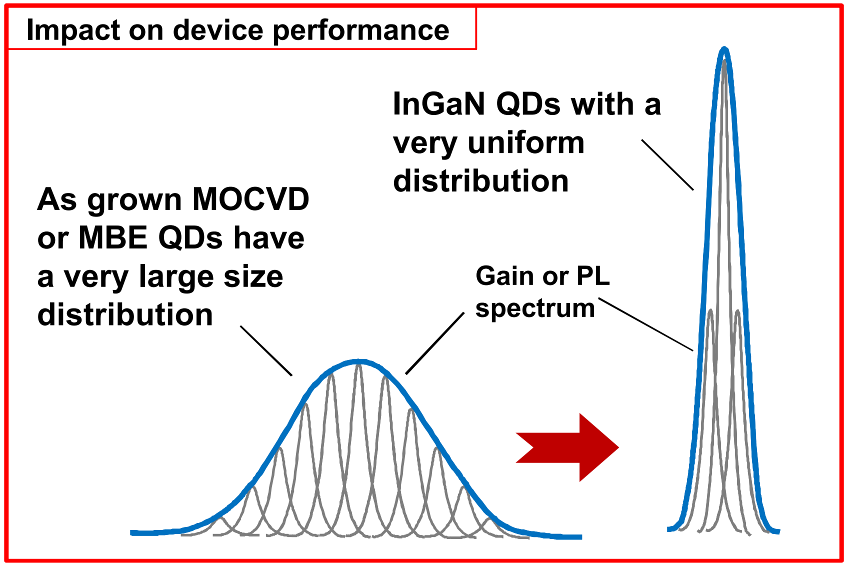
- **Long wavelength visible emitters:**
  - Nanostructure (NWs, QDs) can incorporate more indium
  - High efficiency yellow, orange, and red emission
  - RGB and RYGB emitters require high efficiency yellow to red emitters
- **Visible QD diode lasers:**
  - Lasers for lighting is gaining momentum
  - Low threshold, high efficiency, better temperature performance
  - Monodisperse QDs

InGaN QD laser:
- University of Michigan
- Electrically injected
- 630 nm
- T_o = 236K

Frost et al., IEEE JQE, **49,** 923 (2013).



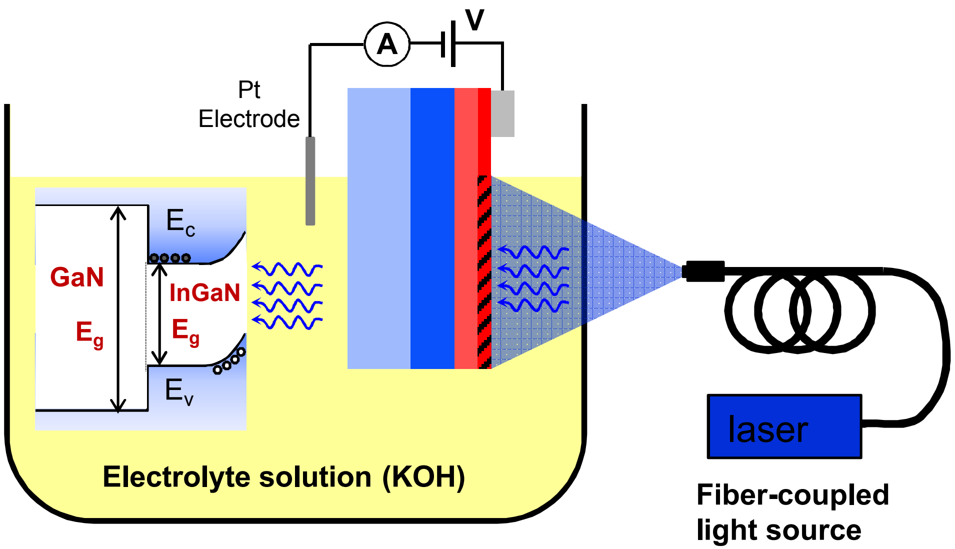
Monodisperse QD Distributions



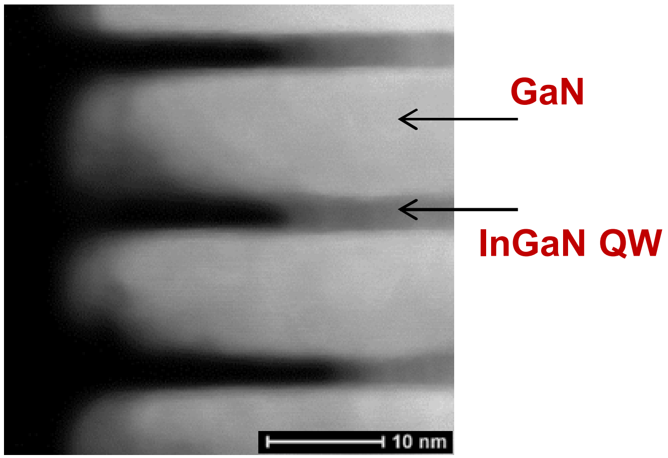
Introduction to InGaN PEC Etching

Photoelectrochemical (PEC) Etching:

- Very few wet etches work for III-nitrides
- Band gap selective (Etch InGaN over GaN)
- Dopant selective, light intensity dependent, etch current can be monitored
- Laser or lamp excitation (Xe arc lamp, tunable ps Ti:S)
- KOH (~0.1M) typically used as electrolyte



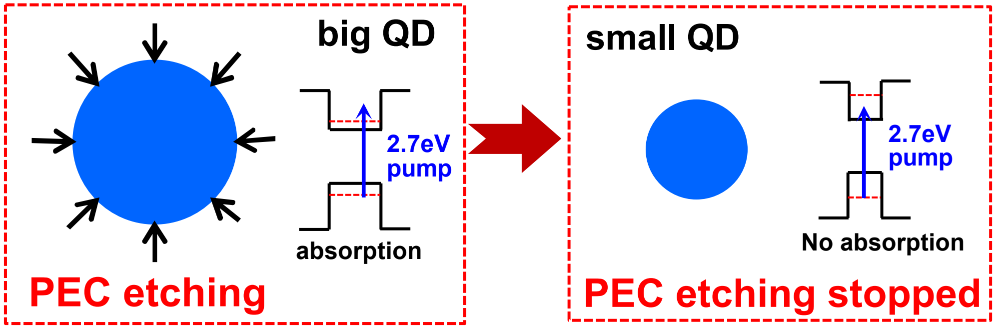
PEC etched InGaN/GaN QWS



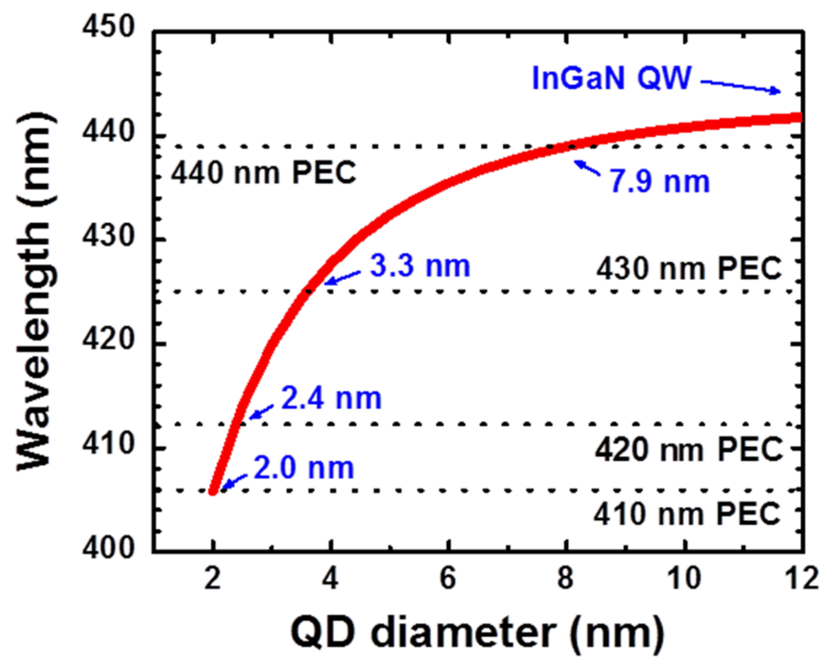
Fabrication of InGaN QDs via PEC etching

Quantum Size Control: Use size quantization to control QD size

Self-limiting PEC etch process:



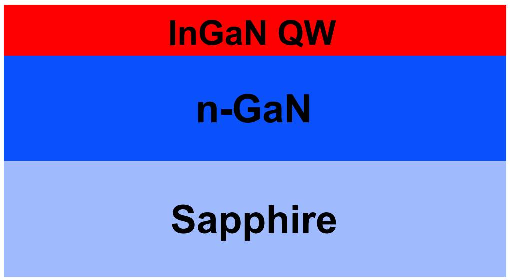
- For QDs, band gap depends on size
- As etch proceeds,
  - QD size gets smaller, band gap goes up
  - Etch terminated for $E_g > E_{photon}$ pump
- Self-terminating etch process
- QD size depends on PEC wavelength
- Monodisperse QD distributions ??



G. Pellegrini, et al., Journal of Applied Physics 97, 073706 (2005).

MOCVD-grown InGaN samples

Uncapped singe InGaN QW



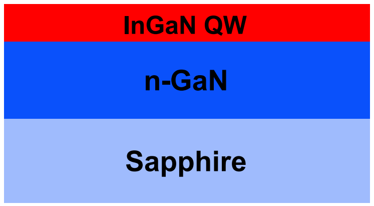
- Grown by MOCVD on sapphire substrates
  - 5 - 20 nm thick InGaN layer
- No InGaN underlayer is used in this sample
- Uncapped single QW sample (14% In):
  - Amenable to surface characterization of QDs
  - TEM, AFM characterization
  - Luminescence weaker than capped sample

Capped singe InGaN QW

- Grown by MOCVD on sapphire substrates
  - 3 nm InGaN QW, 10 nm GaN cap
- InGaN underlayer (~2% In) used in this sample
- Capped single QW sample (14% In):
  - AFM is not useful for capped samples
  - Luminescence brighter than uncapped samples
- Etch is thought to proceed via pits, dislocations

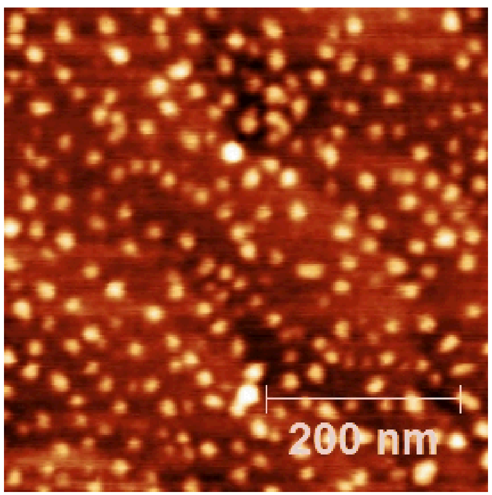
Atomic Force Microscope (AFM) Measurements

Uncapped InGaN QW

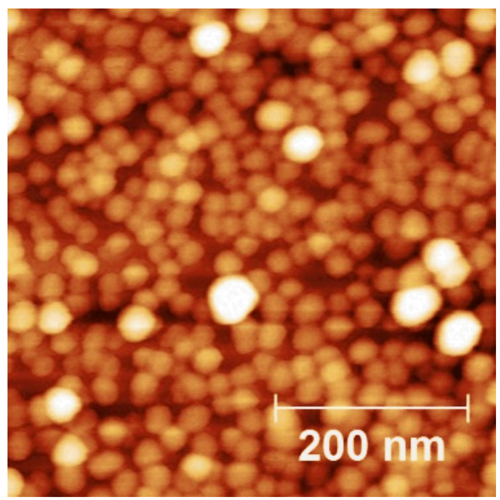


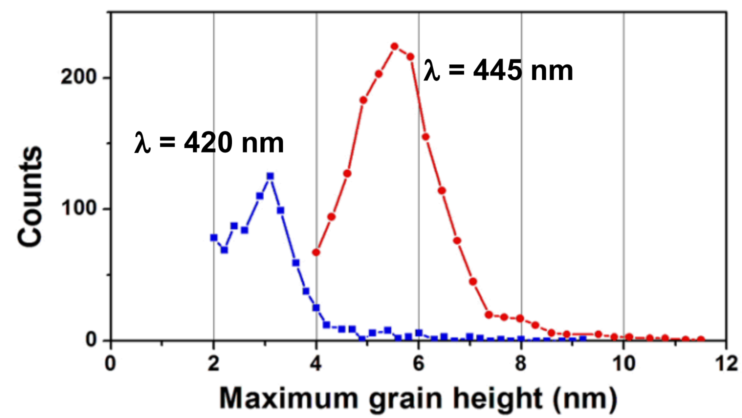
- Samples etched for two hours at 420 nm and 445 nm
  - Laser power density: ~ 3 mW/cm^2
- High dot density: 10^{11}/cm^2
- Some big dots (10-20 nm) remain: due to dislocations?
- QD size depends on PEC etch wavelength

PEC etch→ λ = 420 nm



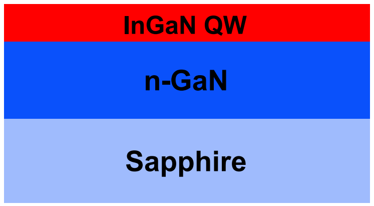
PEC etch → λ = 445 nm



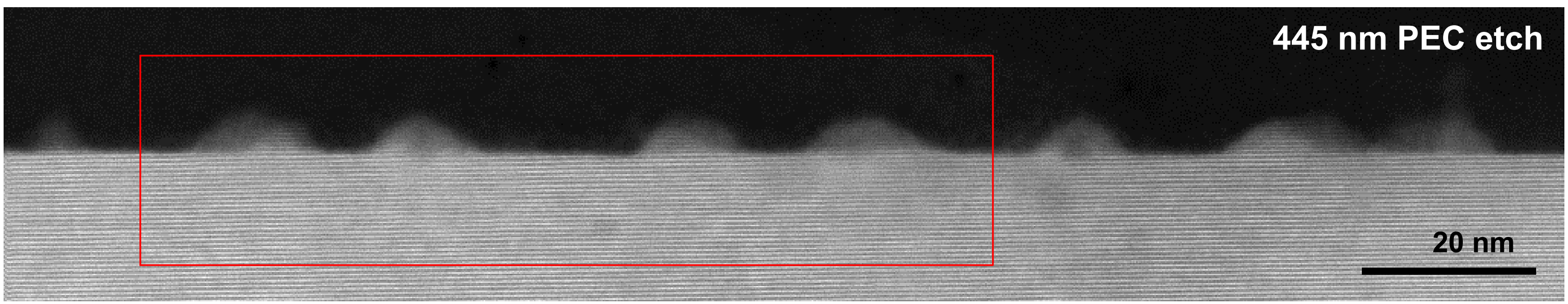


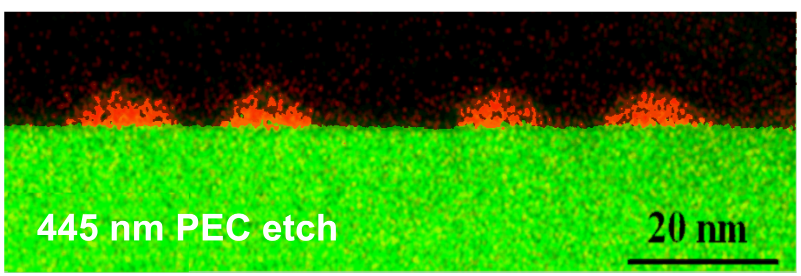
Transmission Electron Microscope (TEM) Images

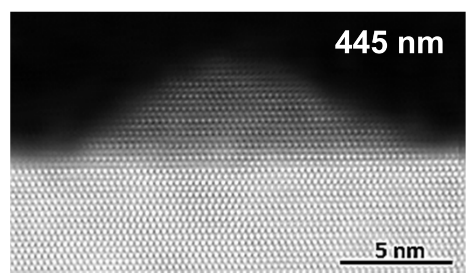
Uncapped InGaN QW

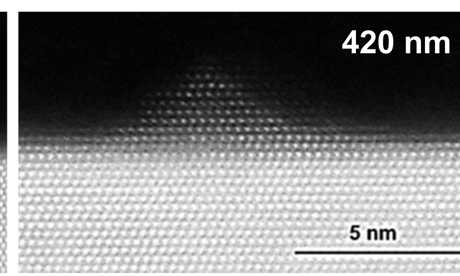


- High-angle annular dark-field (HAADF) TEM images
- Samples etched at 420 nm and 445 nm
- Energy dispersive x-ray mapping
  - QDs on surface are InGaN
  - Red = indium, green=gallium
- InGaN QDs are epitaxial to the underlying GaN
- No underlayer, no cap → PL is not very bright



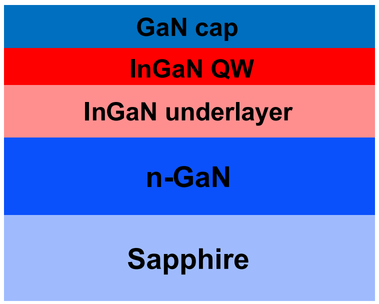






Transmission Electron Microscope Images

Capped InGaN QW

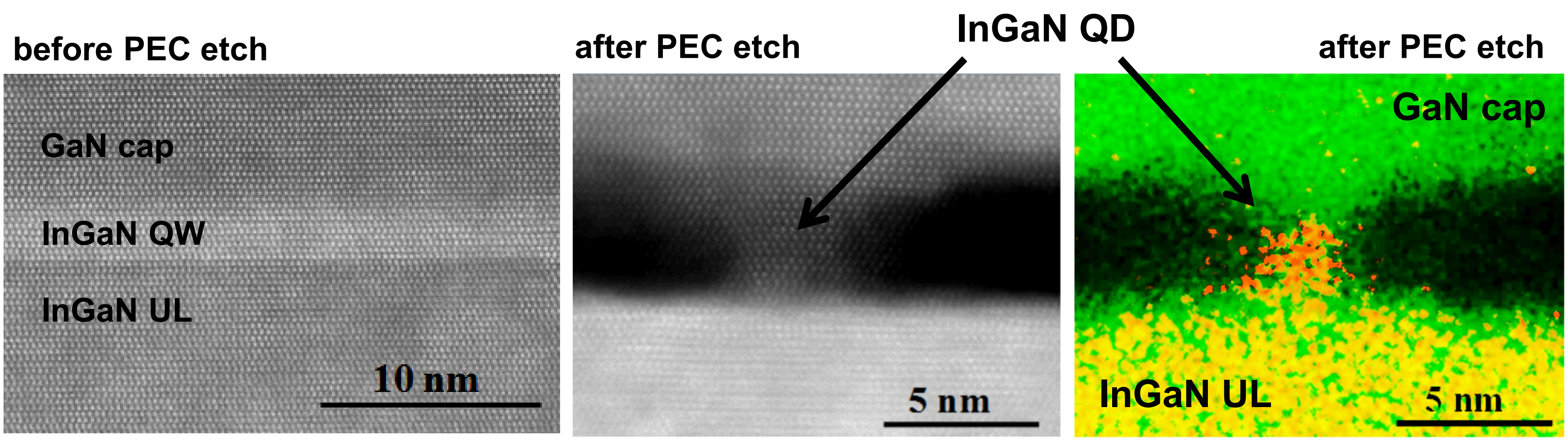


- High-angle annular dark-field (HAADF) TEM images
- Sample etched at 420 nm
- EDX mapping shows that dots are InGaN
- InGaN QDs are epitaxial to the underlying GaN
- 2% InGaN underlayer + GaN cap → PL is much brighter
- GaN cap provides partial passivation

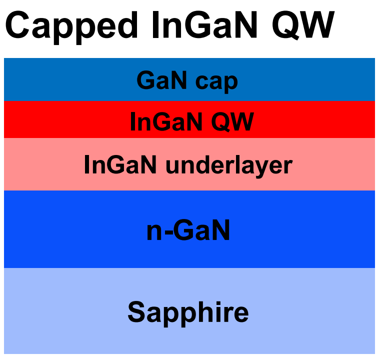
before PEC etch

after PEC etch

after PEC etch



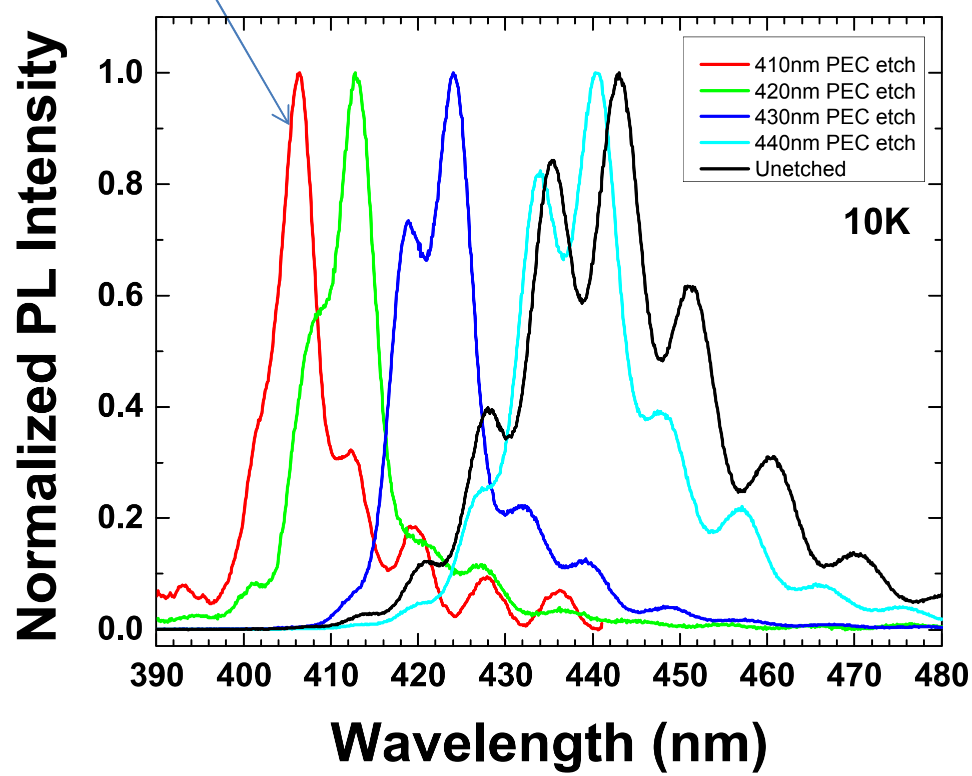
Photoluminescence from fabricated InGaN QDs



Photoluminescence (PL) data:

- 375 nm pump (ps pulsed)
- 10K PL data
- PL wavelength determined by PEC etch wavelength
- PL linewidth: 24 nm → 6 nm
- Quantum size-controlled PEC etching works!

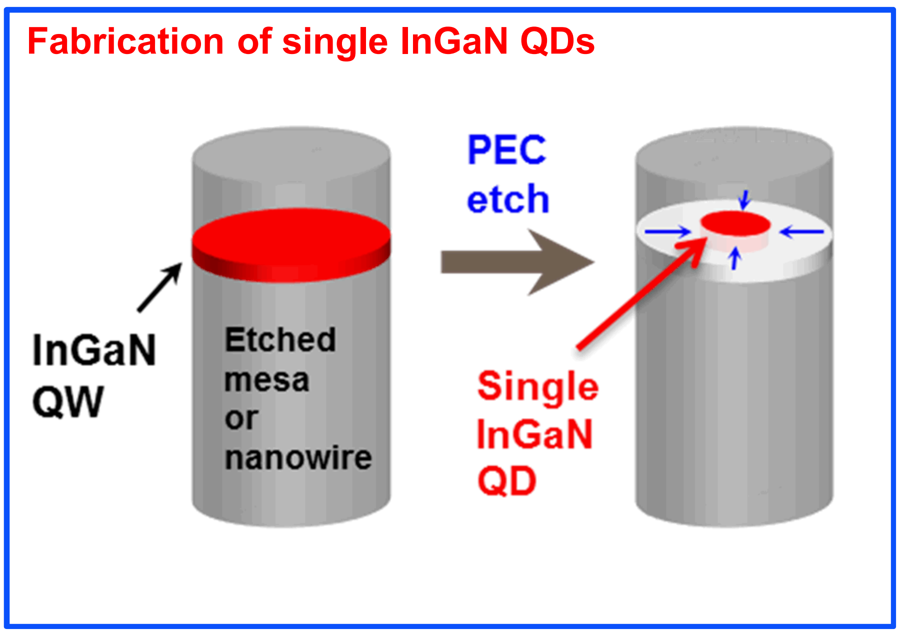
As narrow as **6 nm** FWHM is consistent with a narrowing of the QD size distribution

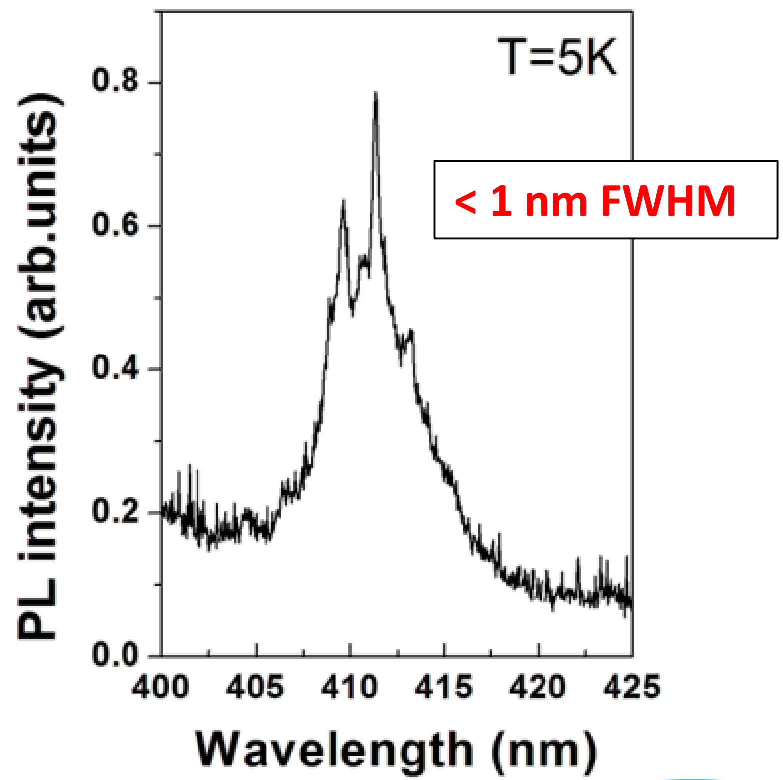


Emission from single InGaN QDs

Capped InGaN QW

- Posts (150 – 200 nm) patterned with e-beam lithography
- Narrow PL emission (<1 nm FWHM) observed
- Fabricate InGaN QDs at deterministic locations
- InGaN QD single photon source





Summary/Conclusions

- Demonstrated fabricated InGaN QDs using PEC etching
  - AFM data indicates 10^{11} QDs per cm^2
  - TEM EDX mapping shows we have InGaN QDs
- Quantum size-controlled etching of InGaN QDs
  - QD size and emission λ determined by PEC wavelength
- PL linewidth reduced from 24 nm to less than 6 nm
  - Shows an improved QD size distribution
- Demonstrated emission from single InGaN QDs
  - Working towards deterministic placement of InGaN QDs