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Deterministic Fabrication of Quantum Dots for Quantum Light Sources Using Selective Photoelectrochemical Etching

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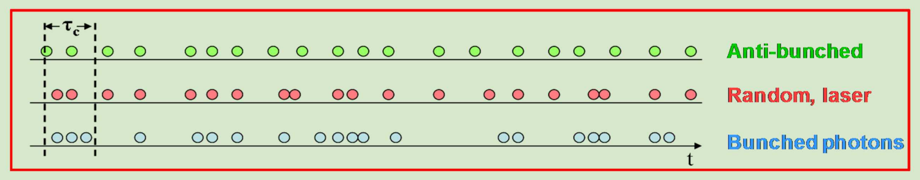
What are Quantum Light Sources ?

- Quantum light sources produce anti-bunched photons
- For example, single photon sources (SPS): photons are emitted one at a time.

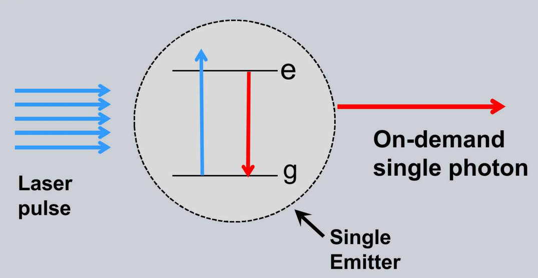


Source: J.S. Lundeen

- They are important for many applications
  - Quantum key distribution
  - Quantum computing
  - Quantum metrology
  - True random number generation

Why III-nitride quantum dots?

- Quantum dots (QD) behave like two-level systems and generate one photon at a time
  - Absorption of one photon saturates the transition and emits one photon upon de-excitation : **On demand**



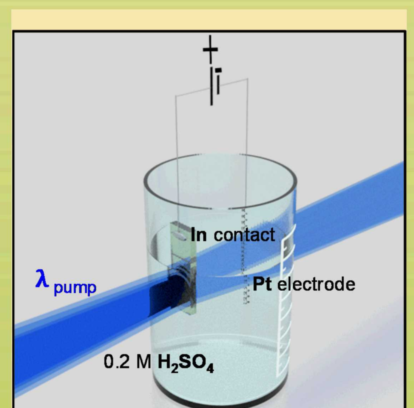
- III-nitrides based QDs are particularly interesting
  - Large exciton binding energy (~ 30 meV) enables **room temperature operation**
  - Short emitter life-time(~ 1ns) enables **fast repetition rate**
  - Path to **electrically** injected operation and **chip-scale** integration
  - Can be fabricated with **controlled size and deterministic placement → Photo electrochemical etching approach**

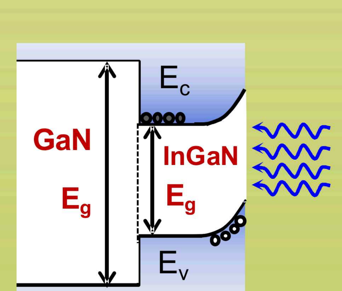
III-nitride system investigated here: InGaN/GaN

Photoelectrochemical Etching

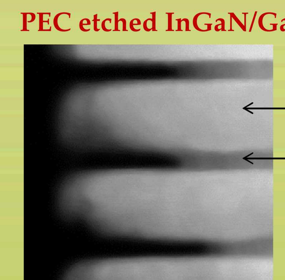
Electrochemical etching of III-nitride material under illuminated conditions

1. The III-nitride material is immersed in a mild acid or base used as electrolye (e.g. ~ 0.1 – 0.2 M KOH or H_2SO_4) under light illumination.
2. Etching proceeds at the semiconductor surface due to oxidation by photoexcited holes.
3. Etching is bandgap selective, dopant selective and light intensity depended – **provides control**





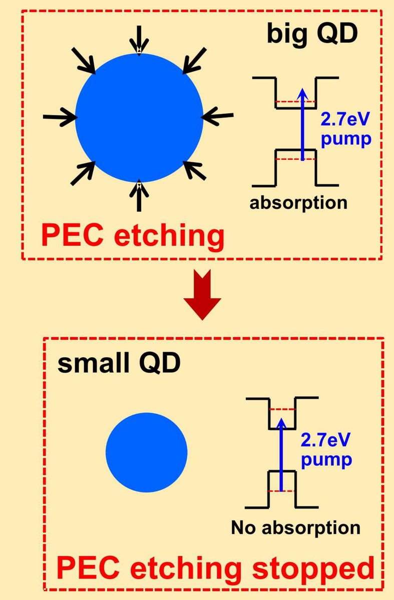
PEC etched InGaN/GaN QWS

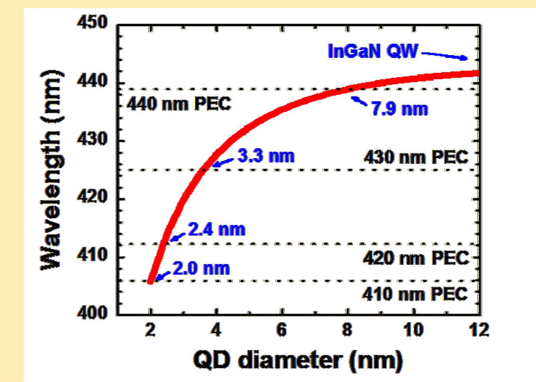


Quantum size control using Photoelectrochemical (PEC) Etching

PEC etch process is self-limiting

- For QDs, enery gap depends on size
- As etch proceeds,
  - QD size gets smaller, band gap goes up
  - Etch terminated for $E_g > E_{photon\ pump}$
- QD size depends on the illumination wavelength
- With narrowband illumination (e.g laser) mondispERSE QDs can be obtained





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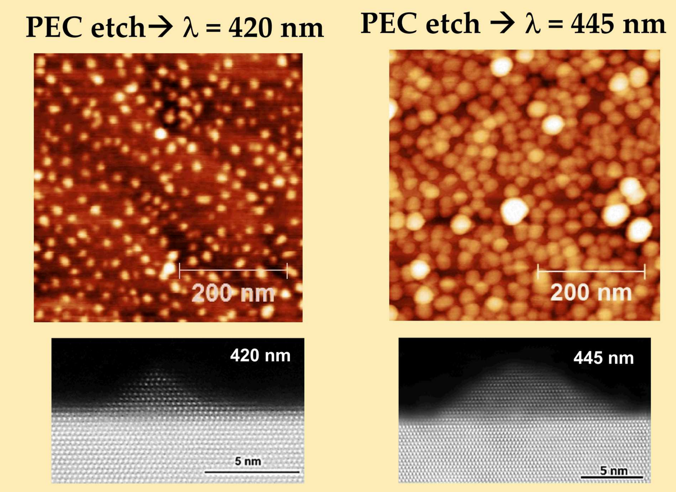
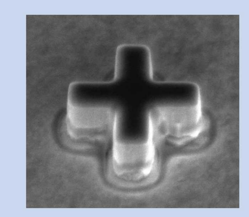


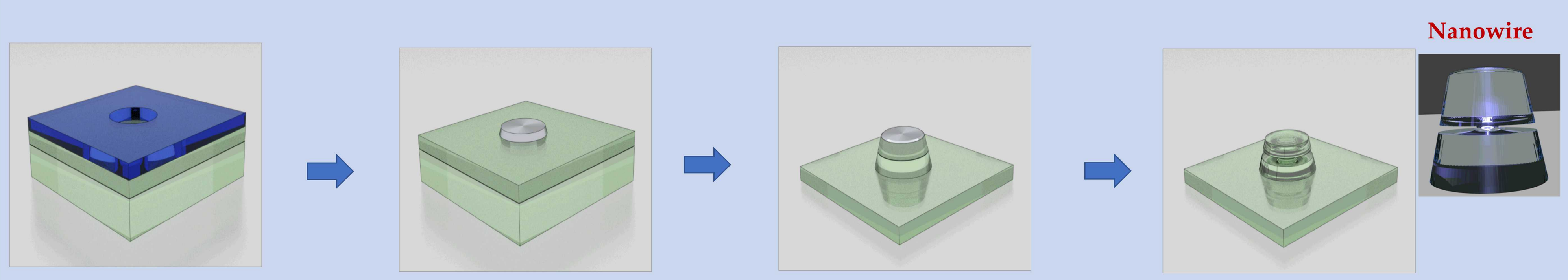
Deterministic placement of PEC etched QDs

To achieve deterministic placement of QDs, an epitaxial stack containing a single quantum well is first patterned using electron beam lithography along with an alignment feature to be used to create subsequent enclosing structure for example a photonic crystal.

Alignment feature

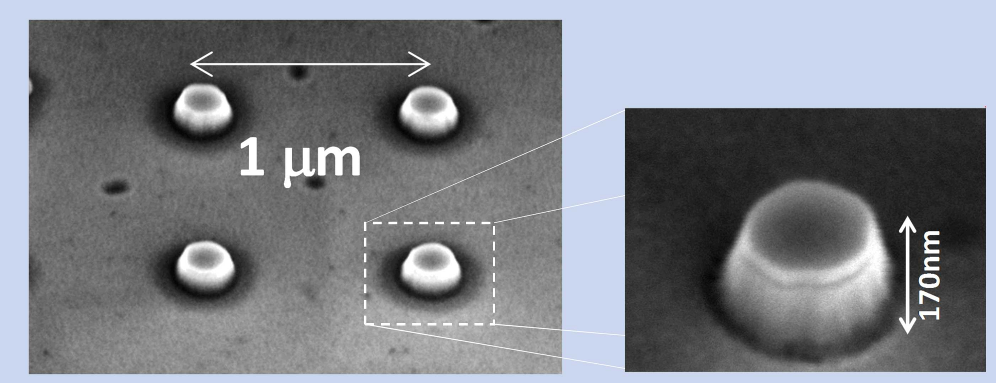


III-nitride Epitaxial structure



1. EBL Patterning and development
2. Nickel deposition and lift-off
3. Cl_2 based dry etch
4. Ni removal followed by PEC etch

Scanning electron microscope image of QD in nanowire

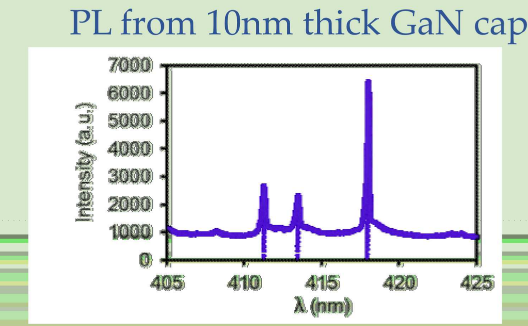


Optical Measurement

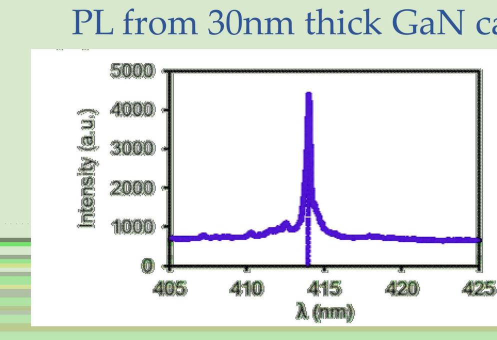
Low temperature photoluminescence collected from PEC etched nanowire

- Multiple or single QD can form depending upon the capping layer thickness

PL from 10nm thick GaN cap



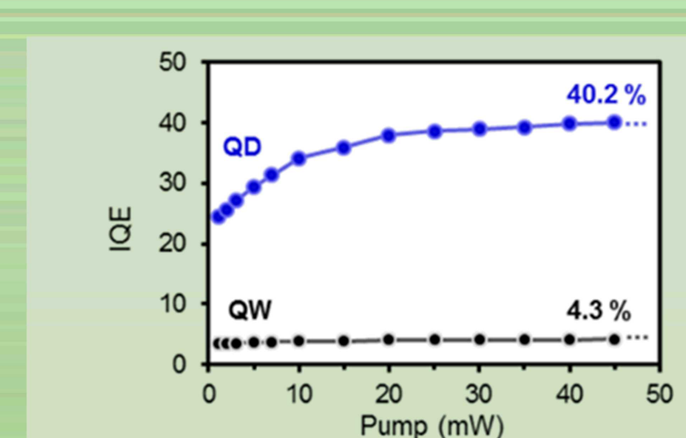
PL from 30nm thick GaN cap



An improvement in internal quantum efficiency is observed for QD vs. the quantum well.

Potential reasons:

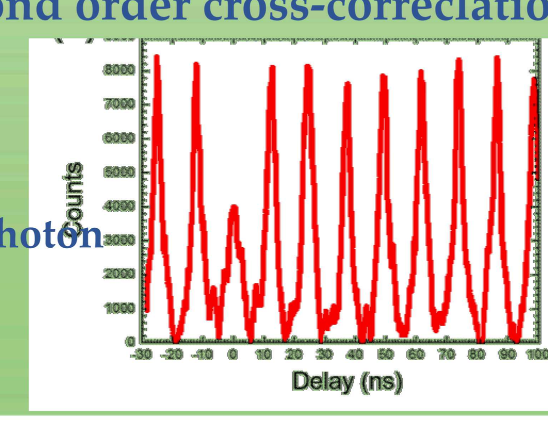
- Strain relaxation and increased carrier confinement in QDs.
- Removal of threading dislocations regions during PEC etching



Hanbury Brown and Twiss (HBT) setup

Second order cross-correclation $g^2(0)$

- $g^2(0) < \sim 0.5$ indicates photon antibunching



Summary

- Quantum light sources are important for quantum information science and technology
- III-nitride based QDs can enable **room temperature, on-demand single photon source**.
- III-nitride QDs can be fabricated at deterministic locations using a combination of aligned patterning and photo electrochemical etch.
- Photon antibunching can be observed in QD in nanowire structures.

References

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2. X. Xiao, A. J. Fischer, G. T. Wang, P. Lu, D. D. Koleske, M. E. Coltrin, J. B. Wright, S. Liu, I. Brener, G. S. Subramania, and J. Y. Tsao, "Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots," Nano Lett. **14**, 5616-5620 (2014).
3. P. D. Anderson, A. J. Fischer, D. D. Koleske, B. P. Gunning, and G. Subramania, "III-nitride photonic crystal emitters by selective photoelectrochemical etching of heterogeneous quantum well structures," Optical Materials Express **8**, 3543-3550 (2018).

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