

Nanophotonic structures for topological photonics and quantum light sources

Ganapathi Subramania

Collaborators: P. Duke Anderson^{*+}, Arthur J. Fischer^{*},
Daniel D. Koleske^{*}

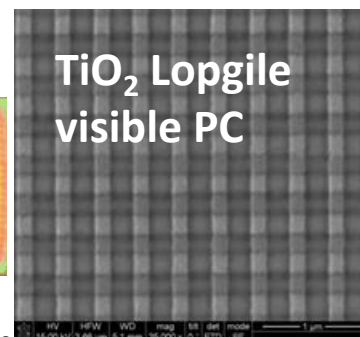
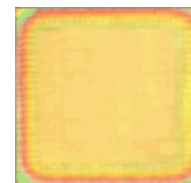
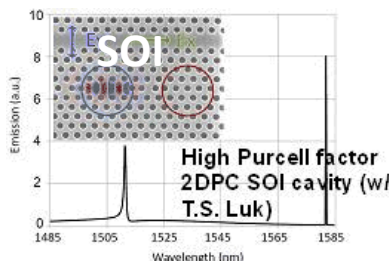
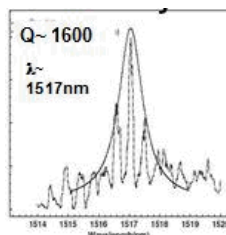
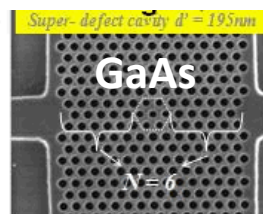
^{*}Sandia National Laboratories, Albuquerque, NM
⁺ University of Southern California, Los Angeles, CA

Jan 28-Feb 2, 2017, SPIE Photonics West
San Francisco, CA

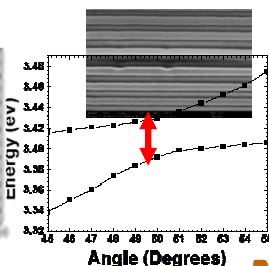
Sandia National Laboratories is a multimission laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Nanophotonics Activity

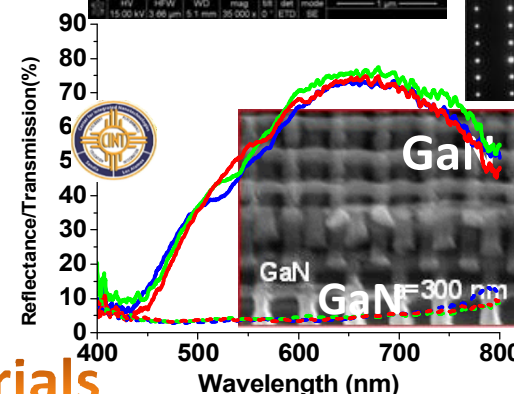
Integrated Photonics, Nanoscale lasing, Strong coupling, Full 3D emission control, Thermal control, Solid State lighting, Energy conversion



Strong coupling
(w/A. Fischer)



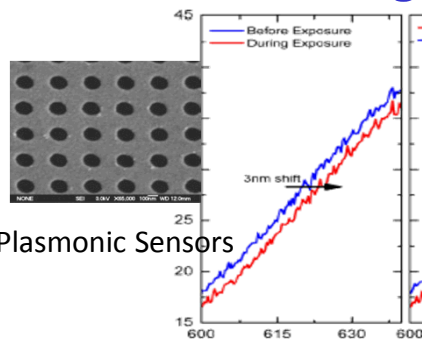
1,2D PC
3D PC
Photonic Nanostructures



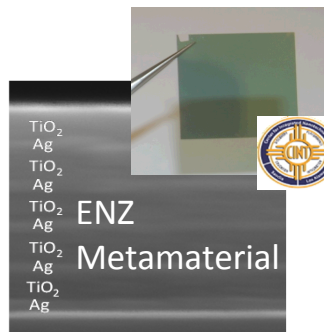
GaN 2DPC laser w/ G. Wang, I. Brener

Metal optics and Metamaterials

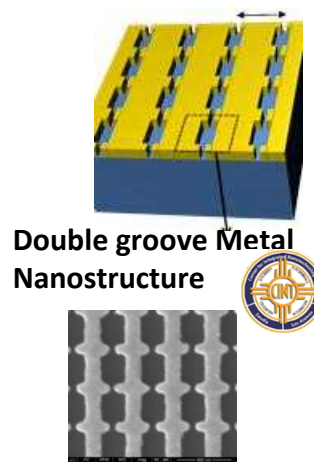
Ultrasubwavelength light control,
Detection, Sensing, Nanocircuitry



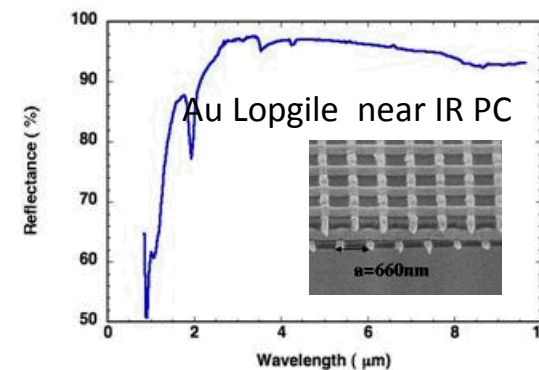
Plasmonic Sensors



ENZ
Metamaterial



Double groove Metal
Nanostructure

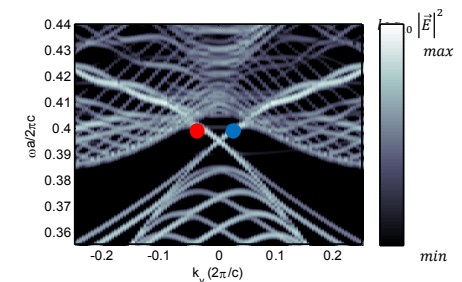
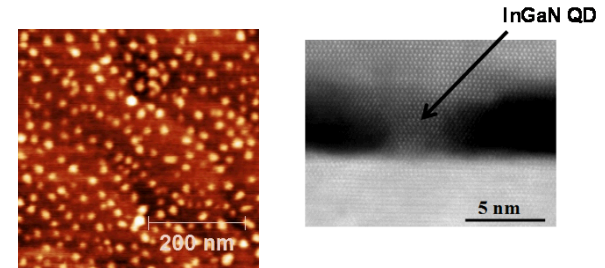


Au Logpile near IR PC

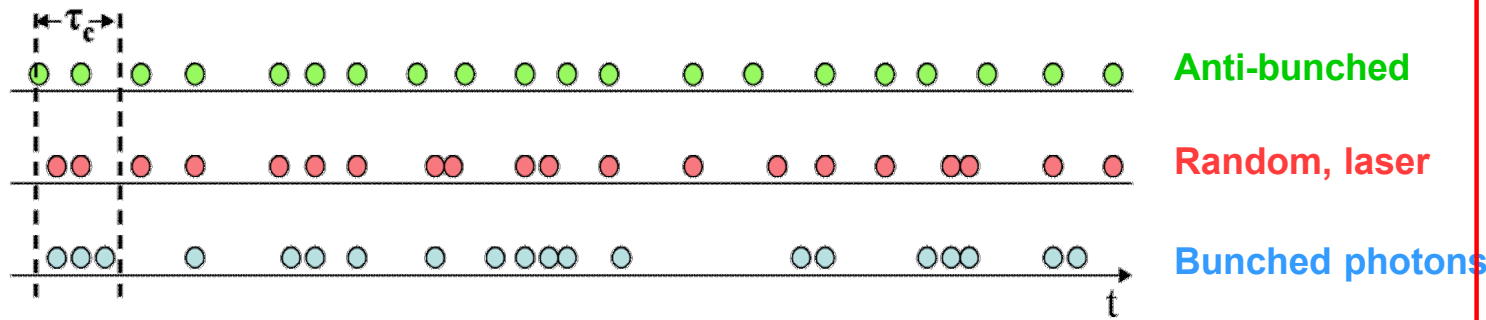
Outline

- Single photon sources
 - III-nitride Quantum dot fabrication
 - Characterization results
 - Summary

- Topological Photonics
 - Design for pseudo spin based topological structure
 - Fabrication approach
 - Summary



Single Photon Source: Photon Statistics



Quantum

$g(2)(t = 0) < 1$
e.g., SPS

Classical

$g(2)(t = 0) \geq 1$
e.g., Thermal, LED, Laser

source: J.S. Lundeen

$$g^{(2)}(\tau) = \frac{\langle I(t + \tau)I(t) \rangle}{\langle I(t) \rangle^2}$$

Quantum communication

- High bit rates than attenuated laser
- Long distance secure comm.
- Quantum repeaters (with indistinguishability)

Quantum metrology

- Measurement of low absorption
- Single molecule level detection (in combination with high efficiency SPD)

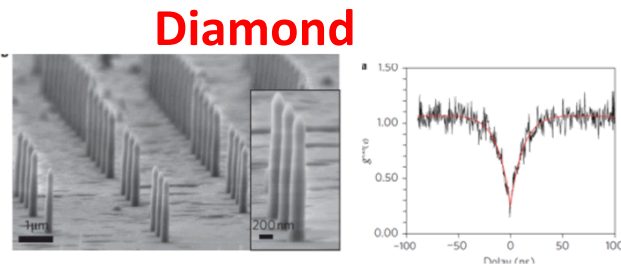
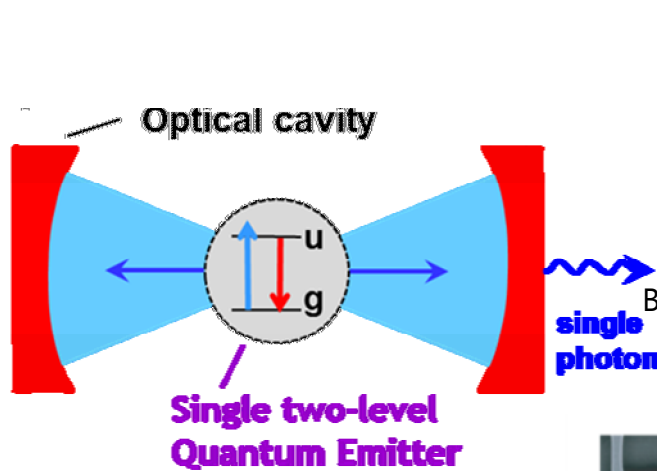
Quantum computing

- Qubit operations
- 'flying' qubits

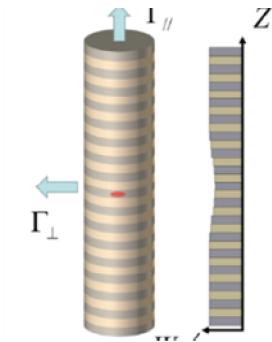
Desired properties of practical single photon sources (SPS)

- ❖ Compact
- ❖ Near 100% probability of emitting single photon : $g_2(0) \sim 0$
- ❖ High single photon rates
- ❖ High extraction or collection
- ❖ Room temperature operation
- ❖ Electrical injection
- ❖ ~ 100% indistinguishability

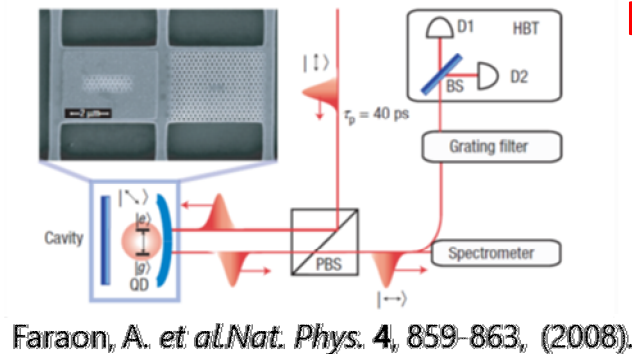
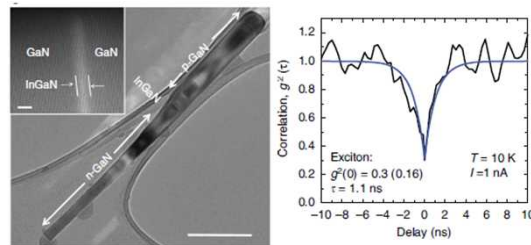
Single Photon Source based on Quantum Dots



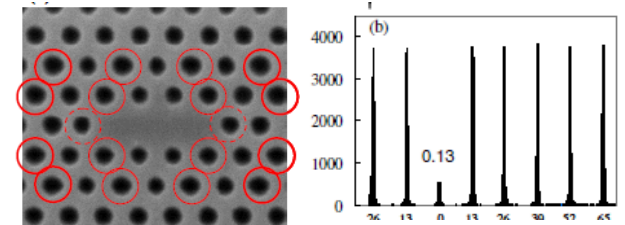
Babinec, T. M. et al. *Nat Nano* **5**, 195-199 (2010).



Portalupi, S. L. et al. *Nano Lett.* **15**, 6290-6294, d (2015).



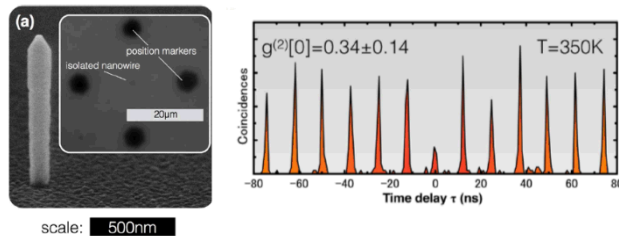
III-V



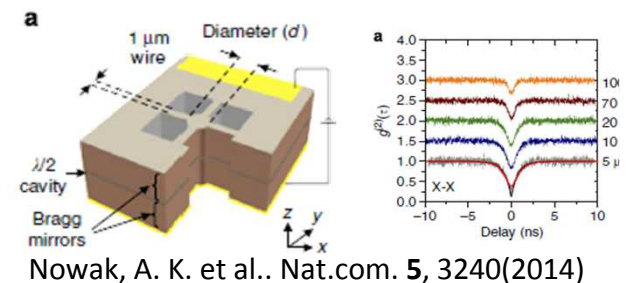
Toishi M., et. al, *J. Opt. Exp.*, **17**, 146185(2009)

Deshpande, S., *Nat.com.* **4**, 1675(2013)

III-N



Holmes, M. J., et. al., *ACS Photonics* **3**, 543-546, (2016).



Nowak, A. K. et al.. *Nat.com.* **5**, 3240(2014)

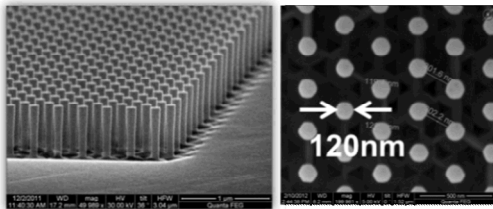
Motivation for InGaN Quantum Dot SPS

Goal: Room temperature, electrically-injected, chip-scale single photon source

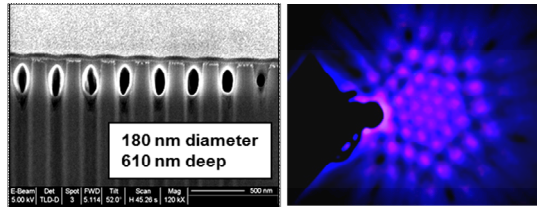
III- N quantum dots have :

- Large exciton binding energy so can enable room temp. operation
- Path to electrical-injection/chip-scale integration
- Deterministic Source: on demand
- Triggered emission within radiative lifetime
 - Short emitter lifetime (~ 1 ns) $\rightarrow$ Fast rep. rate
- *Isolate emission from a single quantum dot*
- *Leverage prior expertise/experience*

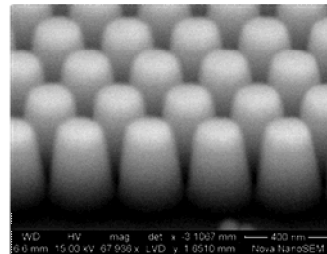
GaN nanowire arrays



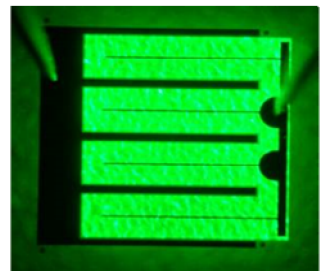
InGaN photonic crystal LEDs



InGaN nano-LED array



Green InGaN LEDs

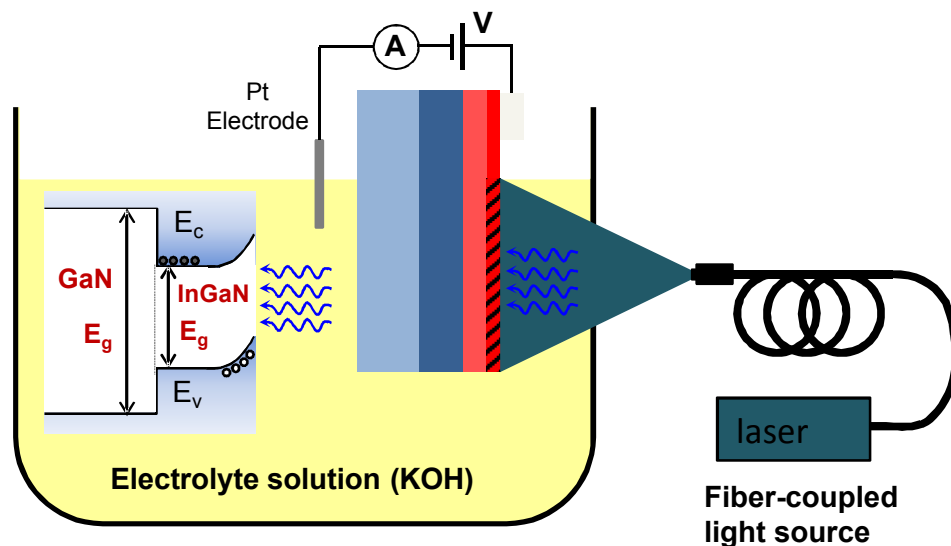


InGaN Photoelectrochemical (PEC) Etching

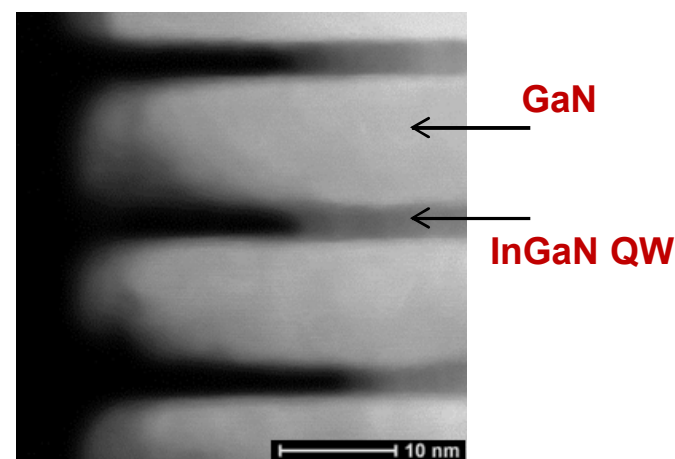
Our approach: Photoelectrochemical etch of MOCVD-grown InGaN QWs

Photoelectrochemical (PEC) Etching:

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



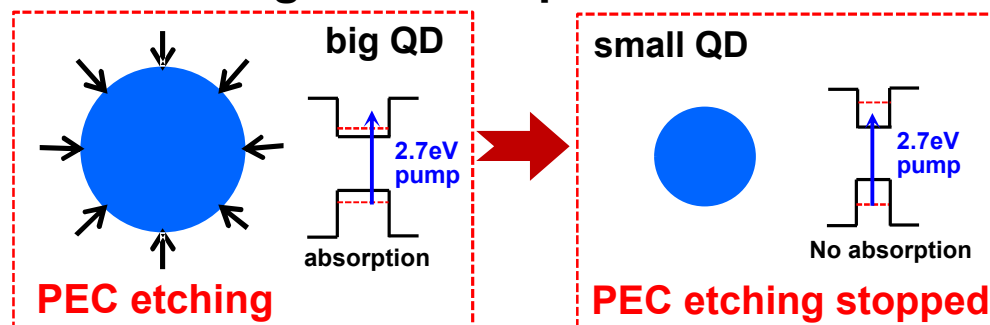
PEC etched InGaN/GaN QWS



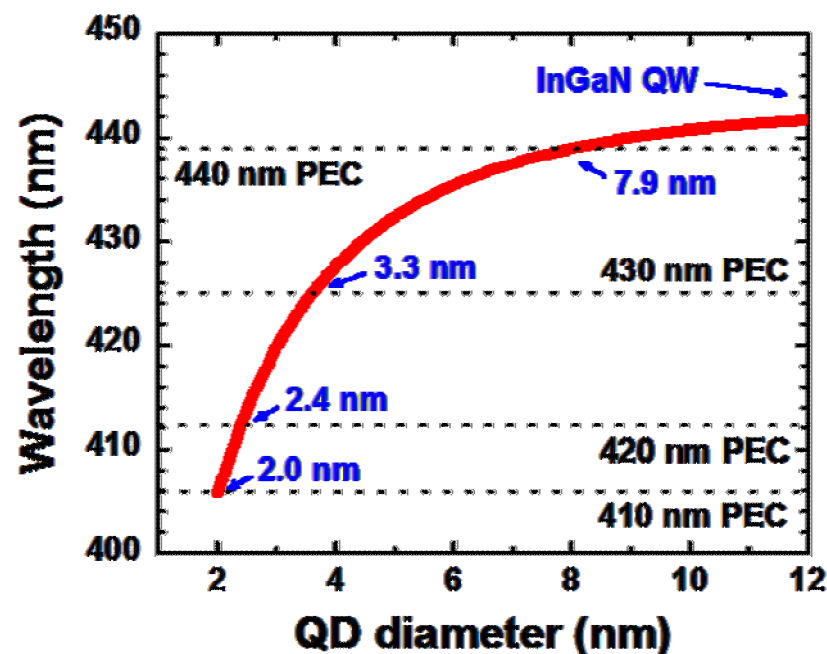
Fabrication of InGaN QDs via PEC etching

Quantum Size Control: Use size quantization to control QD size

Self-limiting PEC etch process:



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



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

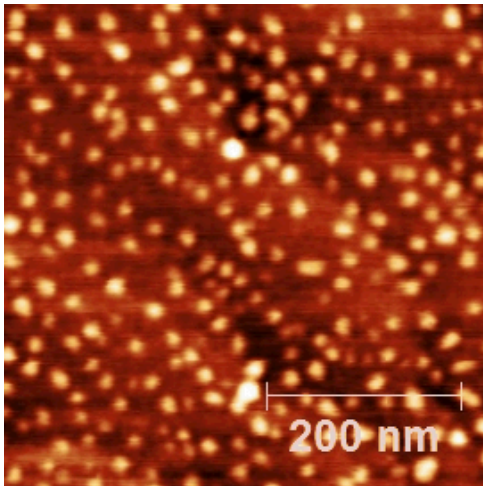
Atomic Force Microscope (AFM) Measurements

Uncapped InGaN QW

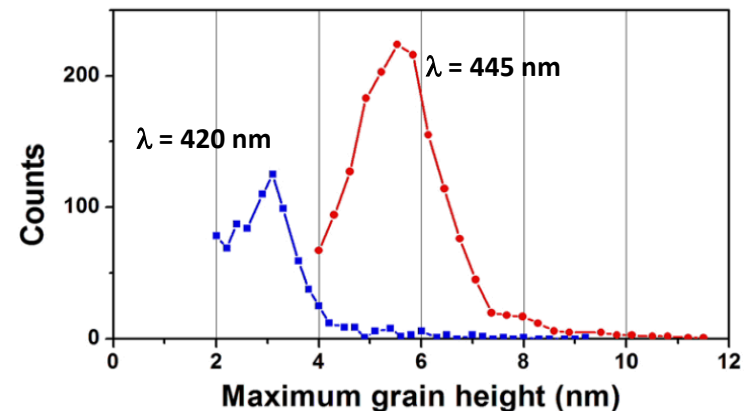
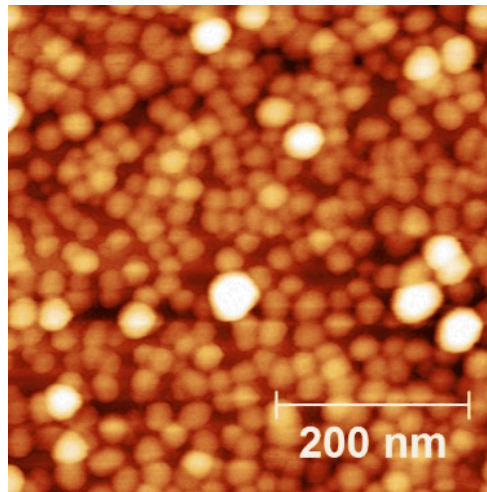


- Samples etched for two hours at 420 nm and 445 nm
 - Laser power density: $\sim 3 \text{ mW/cm}^2$
- High dot density: $10^{11}/\text{cm}^2$
- QD size depends on PEC etch wavelength
- Some big dots (10-20 nm) remain: due to dislocations?

PEC etch $\rightarrow \lambda = 420 \text{ nm}$



PEC etch $\rightarrow \lambda = 445 \text{ nm}$



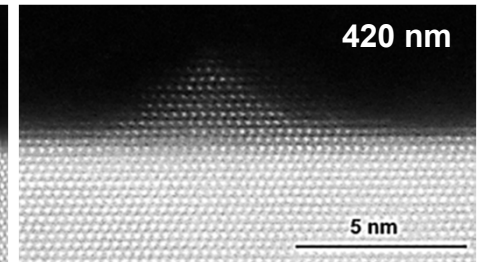
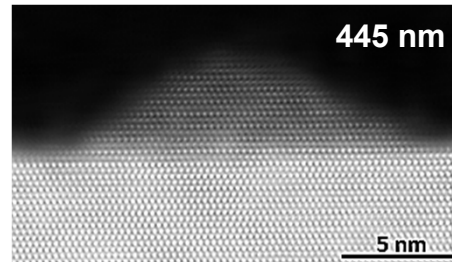
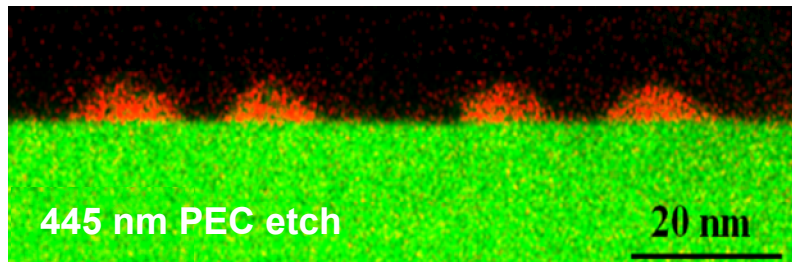
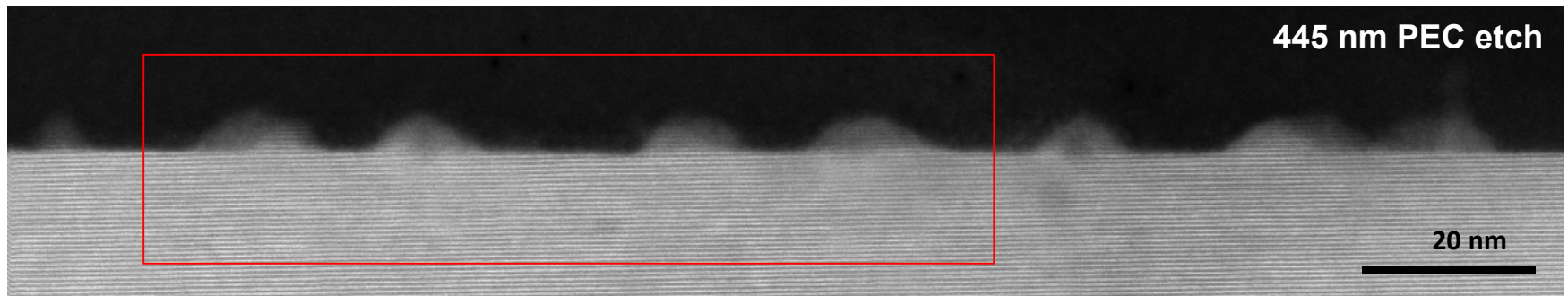
Transmission Electron Microscope (TEM)

Images

Uncapped InGaN QW

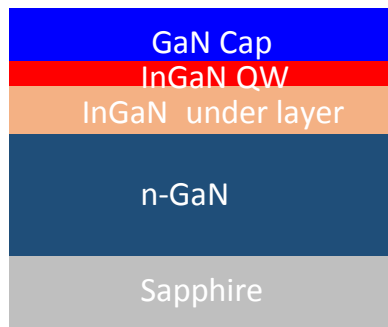


- High-angle annular dark-field (HAADF) TEM images
- Samples etched at 420 nm and 445 nm
- Energy dispersive x-ray mapping
 - QDs on surface are InGaN
 - Red = indium, green=gallium
- InGaN QDs are epitaxial to the underlying GaN
- No underlayer, no cap → PL is not very bright

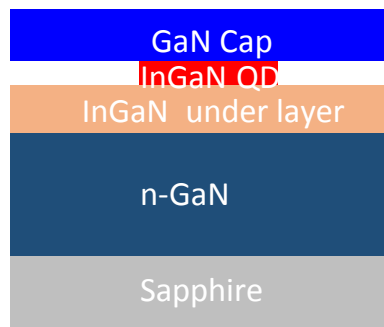


Transmission Electron Microscope Images

Capped InGaN QW

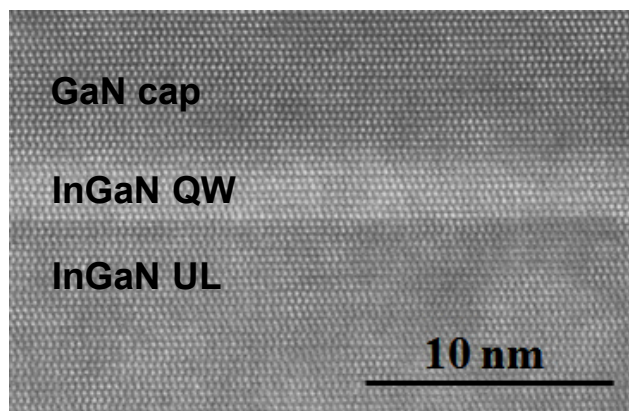


InGaN QD

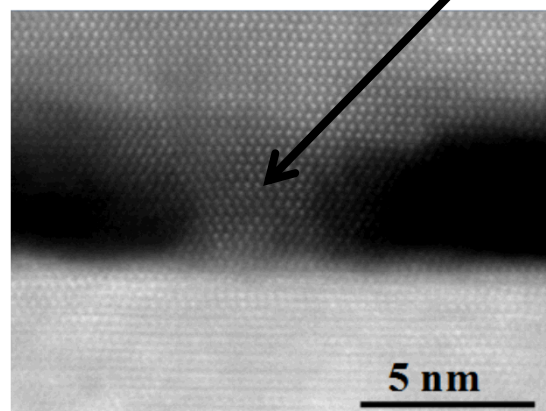


- High-angle annular dark-field (HAADF) TEM images
- Sample etched at 420 nm
- EDX mapping shows that dots are InGaN
- InGaN QDs are epitaxial to the underlying GaN
- 2% InGaN underlayer + GaN cap
- GaN cap provides partial passivation

before PEC etch

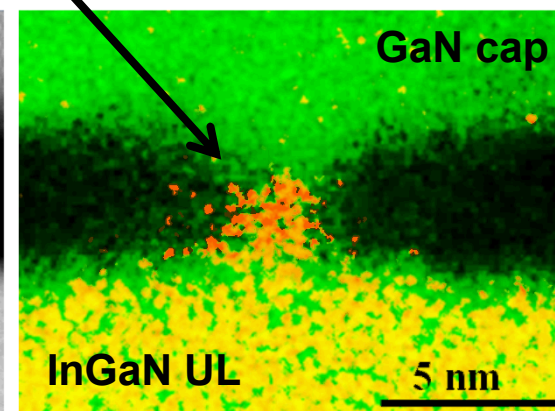


after PEC etch



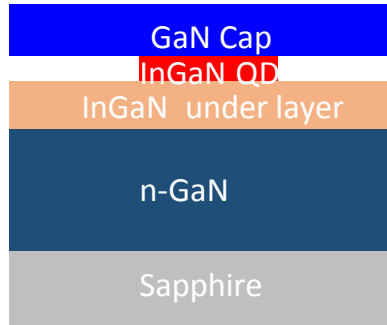
InGaN QD

after PEC etch



Photoluminescence from fabricated InGaN QDs

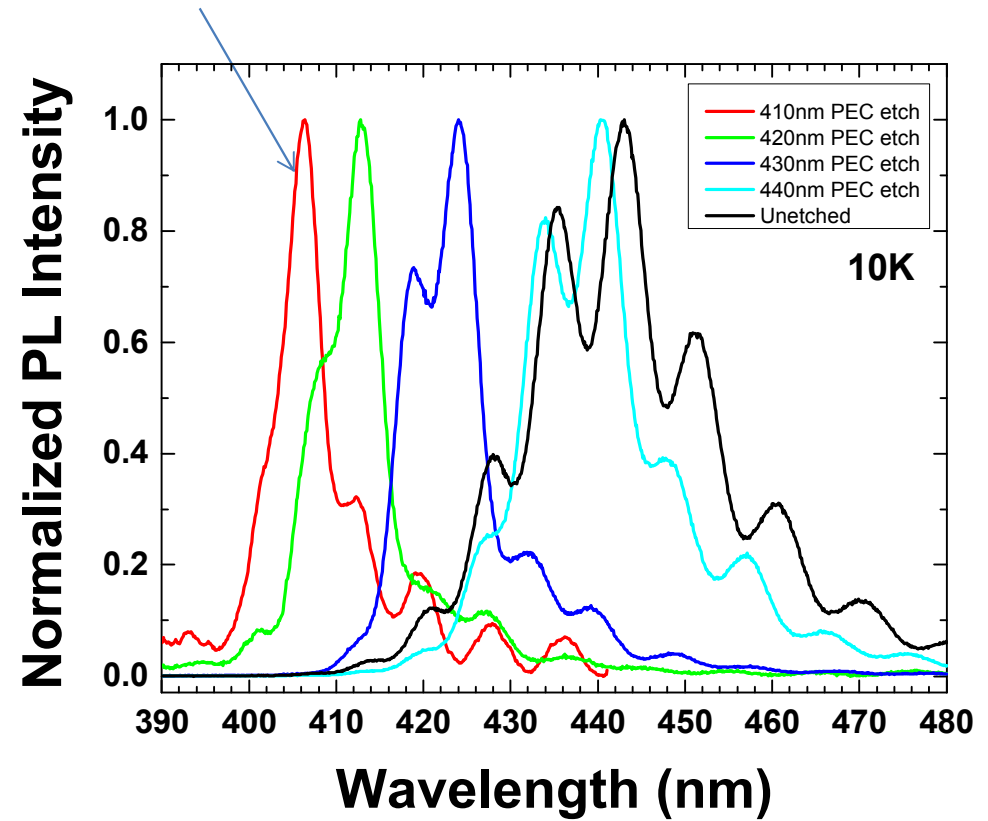
Capped InGaN QW



Photoluminescence (PL) data:

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

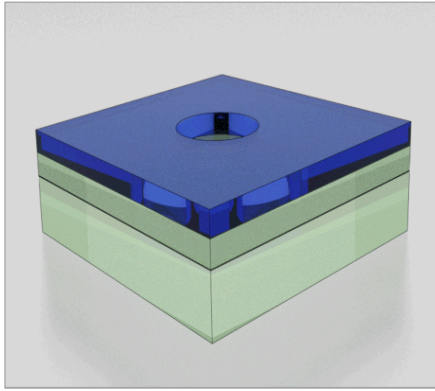
As narrow as **6 nm** FWHM is consistent with a narrowing of the QD size distribution



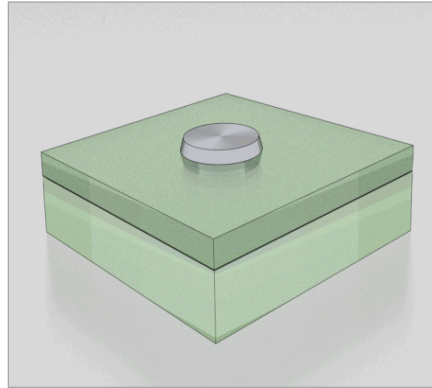
Patterned fabrication of InGaN QDs

➤ Deterministic placement

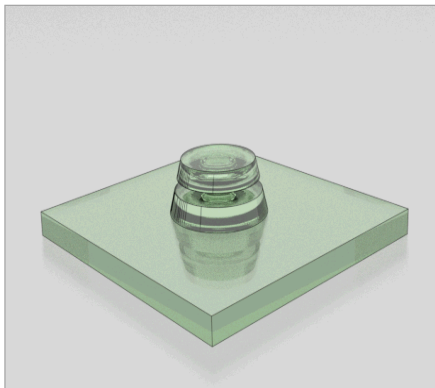
EBL Patterning



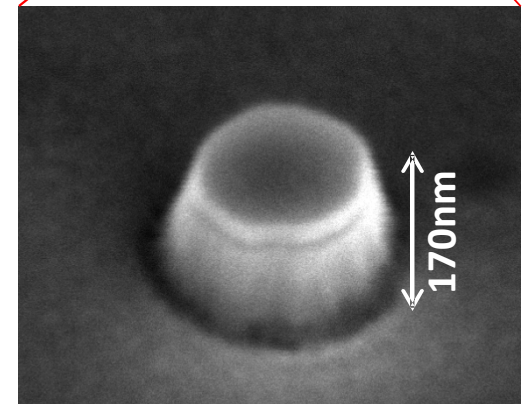
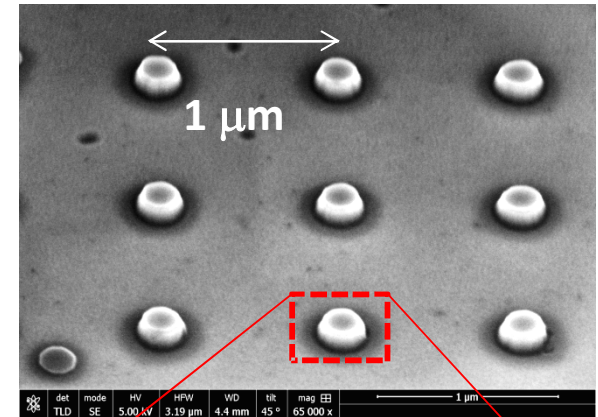
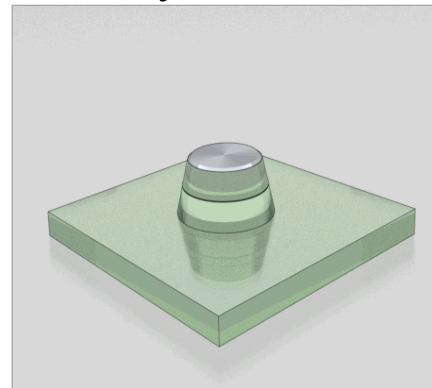
Metal Evaporation + Liftoff



Ni removal + PEC Etch



Dry Etch



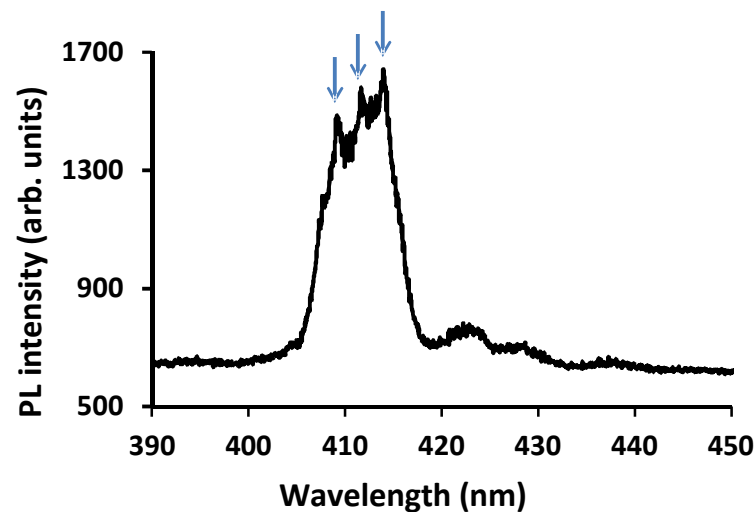
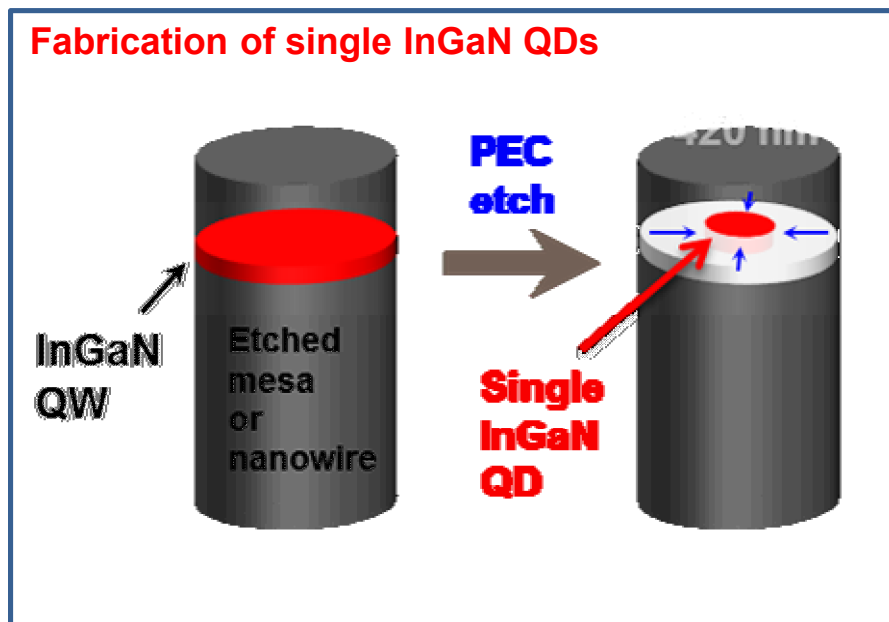
Emission from single InGaN QDs

Capped InGaN QW



- Posts (150 – 200 nm) patterned with e-beam lithography
- Fabricate InGaN QDs at deterministic locations
- GaN cap ~ 10nm
- Narrow peaks emerge revealing QD formation

Fabrication of single InGaN QDs



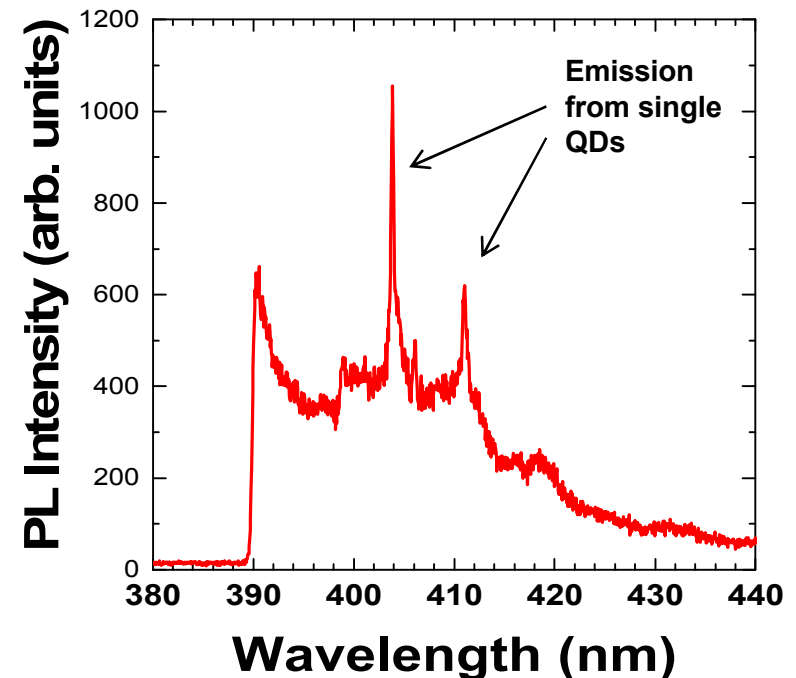
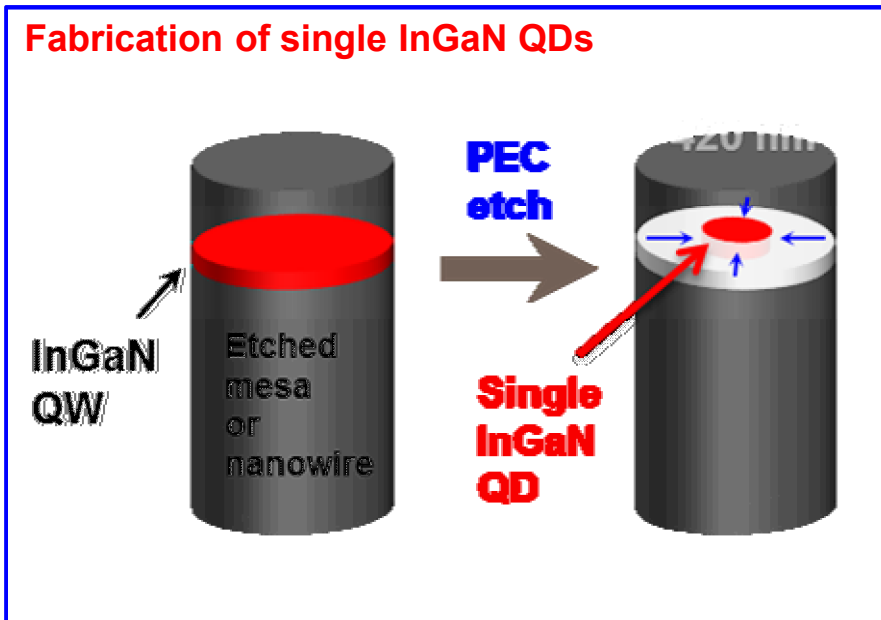
PL from InGaN QDs (thicker GaN cap)

Capped InGaN QW



- Posts (150 – 200 nm) patterned with e-beam lithography
- Thicker GaN capping layer (~ 30 nm)
- Narrow PL emission (<1 nm FWHM) observed
- Better ratio of single QD mission to background

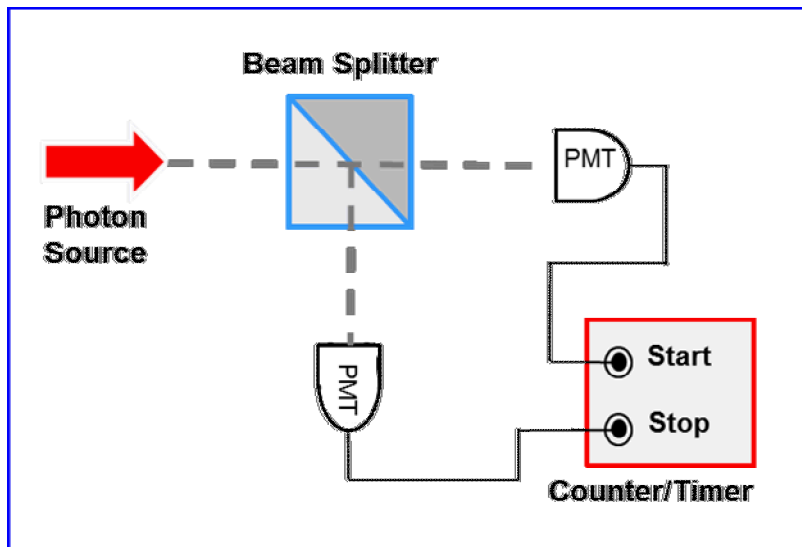
Fabrication of single InGaN QDs



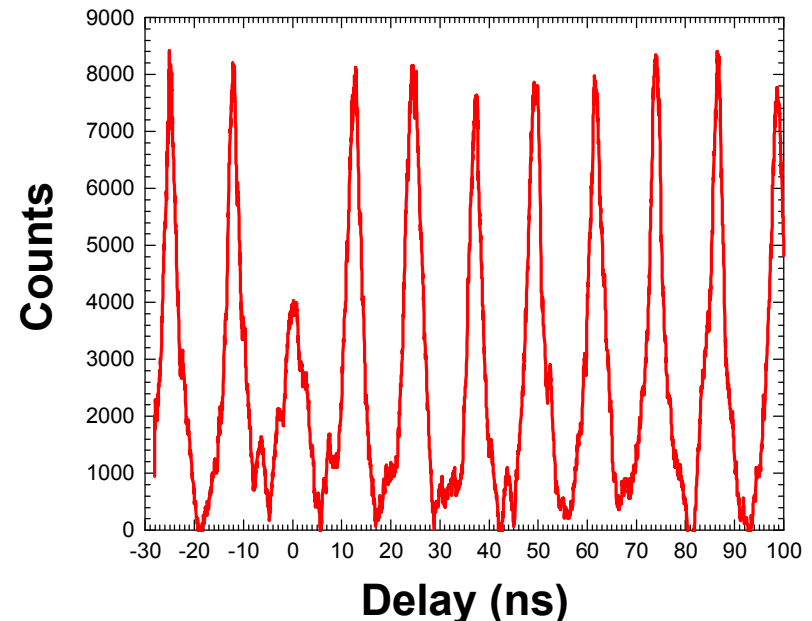
Single Photon Measurement: HBT experiment

- Observation of antibunching : $g_2 \sim 0.5$ for PEC-etched InGaN QDs
- Next steps:
 - Thicker GaN cap
 - Reduce nanowire radius
 - Emission rate enhancement
 - Enhanced light extraction

HBT Experimental Set-up

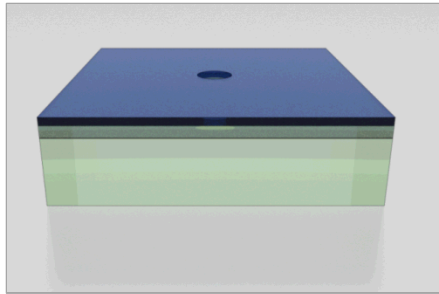


Pulsed g_2 data

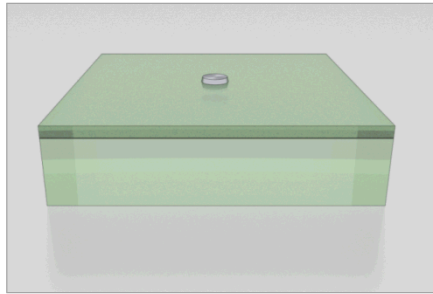


Nanofabrication Approach

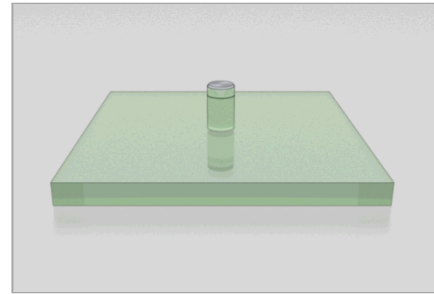
EBL Patterning



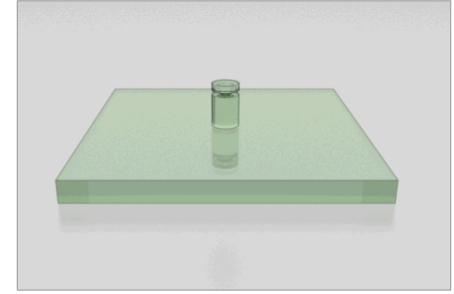
Metal Evap. + Liftoff



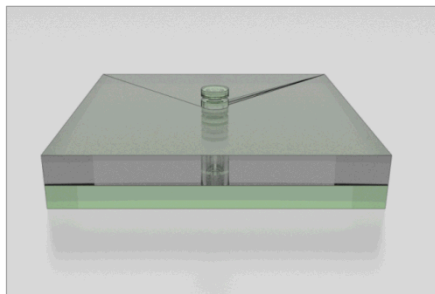
Dry + Wet Etch



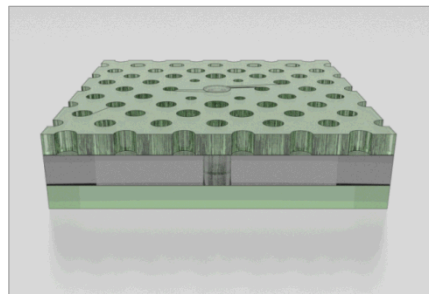
PEC Etch



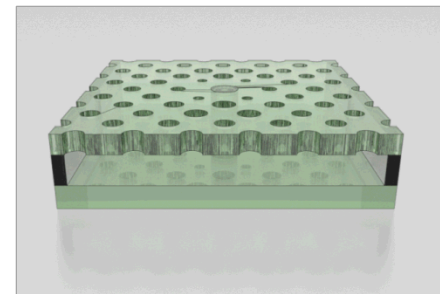
Spin-coat FOX16



TiO₂ dep. + EBL



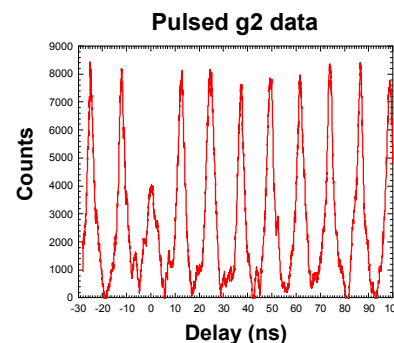
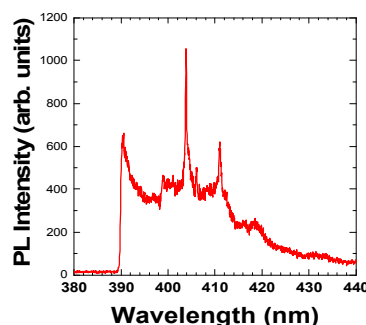
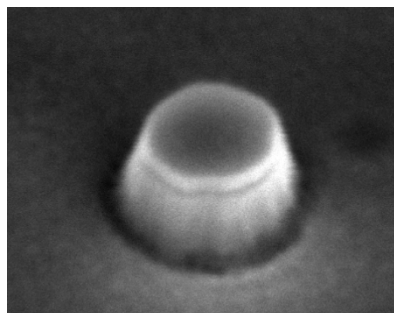
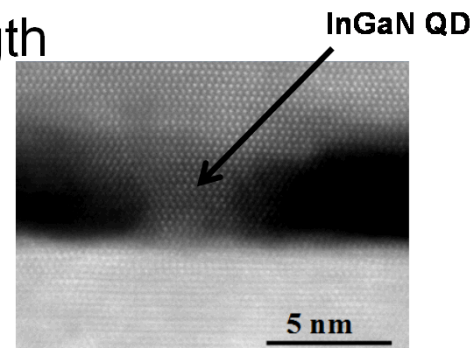
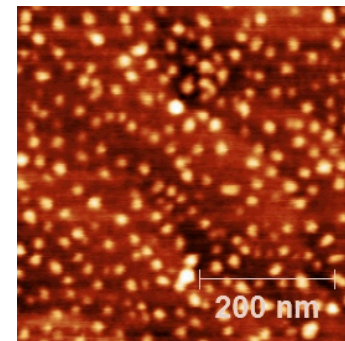
Membrane formation



Potentially all III-nitride solution is possible but fabrication is more challenging

Summary

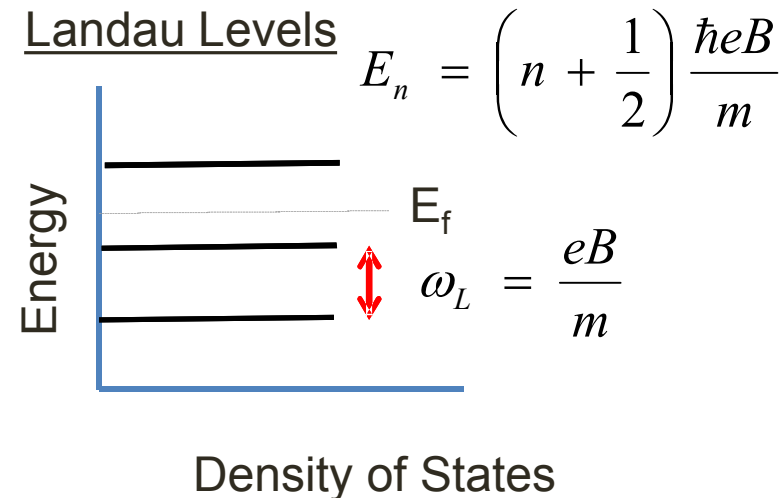
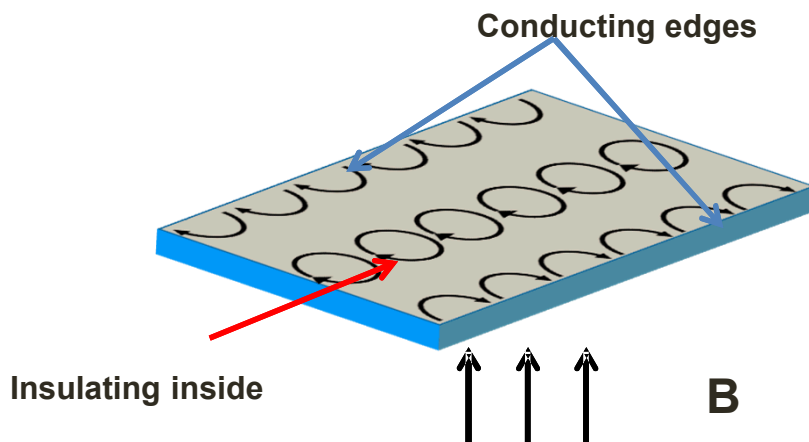
- **Motivation for Single Photon Source**
 - Quantum information
- **Quantum size controlled PEC etching**
 - TEM EDX mapping shows we have InGaN QDs
 - Quantum wells are etched to make QDs
 - QD size and emission λ determined by PEC wavelength
- **Emission from single InGaN QDs in post samples**
 - Narrow linewidth emission (<0.3 nm)
 - Pulsed g2 measurement showing $g2 \sim 0.5$



Electronic Topological Insulators : Systems exhibiting Quantum Hall Effect → 2DEGs

Time reversal symmetry is broken by applying magnetic (B) field

- Discrete highly degenerate Landau Levels
 - Conducting edge states within insulator gap
 - Topologically protected “one way” electronic transport
- *Needs high B fields*
 - *Low temperatures*

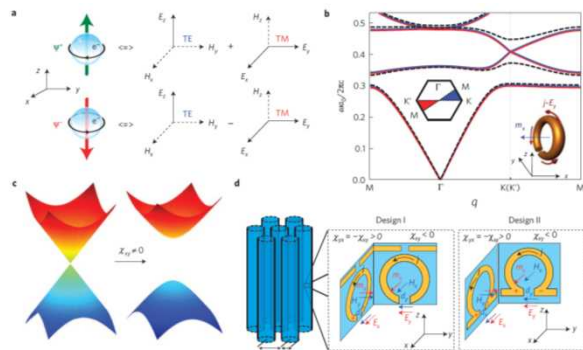


It turns out appropriately designed photonic structures can exhibit similar topological properties too!

F. D. M. Haldane and S. Raghu, Phys. Rev. Lett. **100** (1), 013904 (2008).

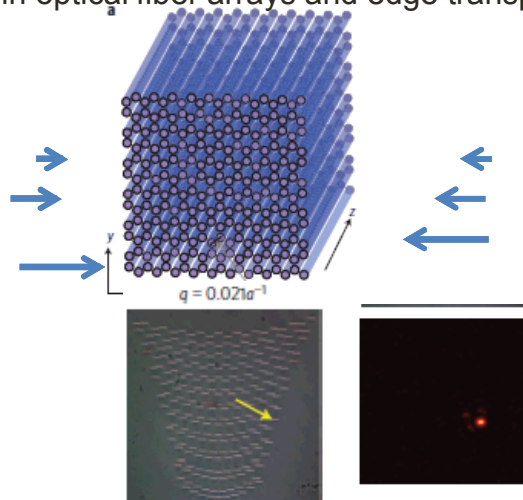
Topological Photonics Research Activities

Metamaterial Photonic Topological Insulator



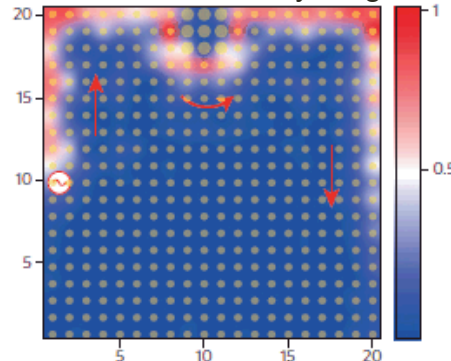
A. B. Khanikaev et.al. *Nat Mater* **12** (3), 233-239 (2013).

Strain induced pseud mag. field in optical fiber arrays and edge transport



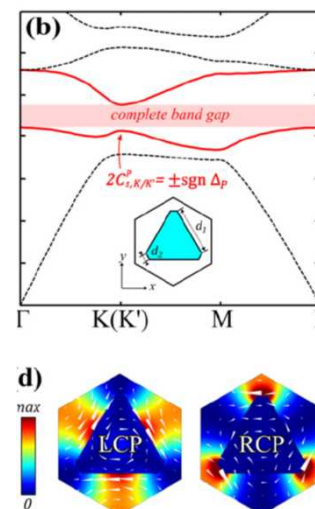
M. Rechtsman et.al. *Nat. Phot.* **7** (2013)

Simulation of Oneway edge transport



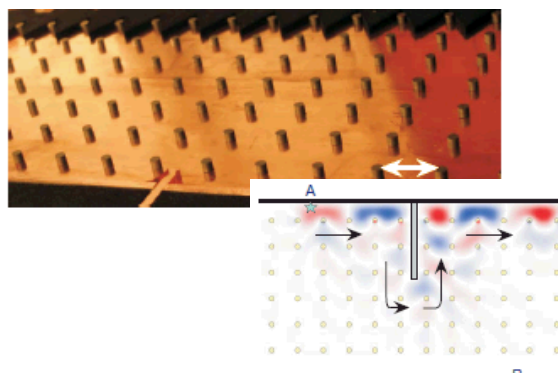
K.Fang, Z. Yu , S.H.Fan , *Nat. Phot.* **6** , (2012)

Valley hall Photonic Topological Insulator

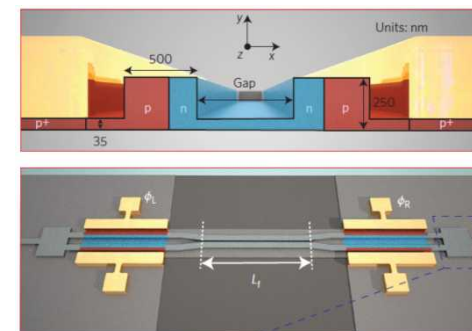


M. Tzuhuan and S. Gennady, *New Journal of Physics* **18** (2), 025012 (2016).

One- way scatter transport at microwave frequency ~ 4GHz in 2DPCs



Z. Wang et. al. *Nat.* **461** (2009)



L. D. Tzuang, et. al. *Nat Photon* **8** (9), 701-705 (2014).

Topological Photonics Spin Hall in Dielectric PC

PRL 114, 223901 (2015)

PHYSICAL REVIEW LETTERS

week ending
5 JUNE 2015

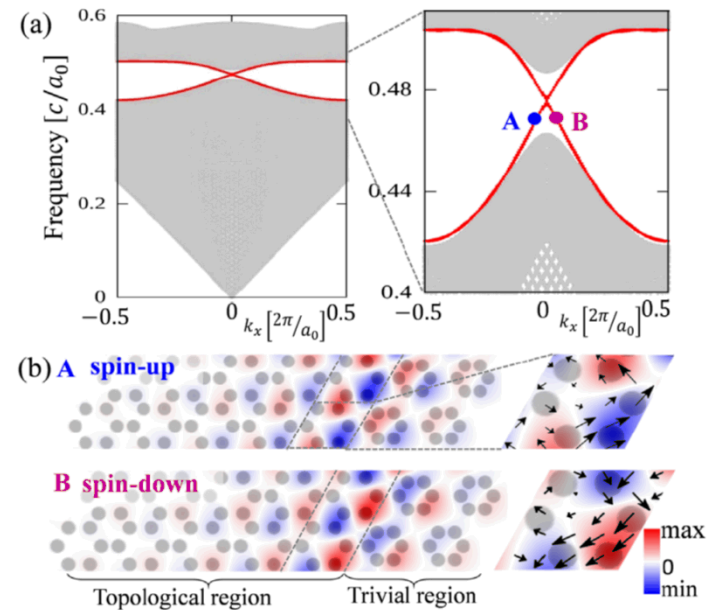
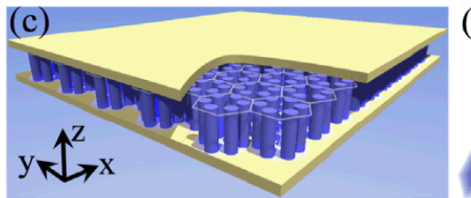
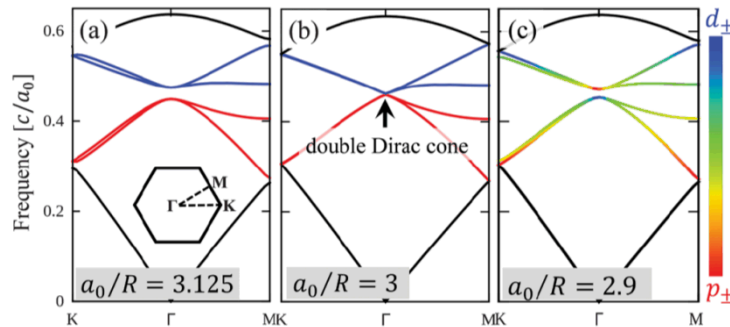
Scheme for Achieving a Topological Photonic Crystal by Using Dielectric Material

Long-Hua Wu and Xiao Hu*

*International Center for Materials Nanoarchitectonics (WPI-MANA), National Institute for Materials Science,
Tsukuba 305-0044, Japan*

Graduate School of Pure and Applied Sciences, University of Tsukuba, Tsukuba 305-8571, Japan

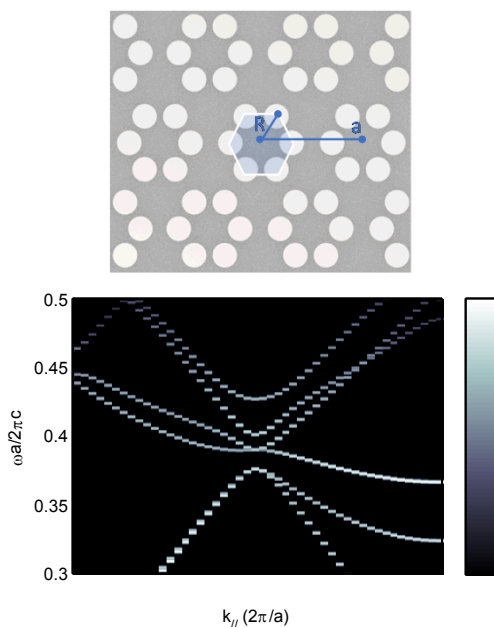
(Received 10 February 2015; published 3 June 2015)



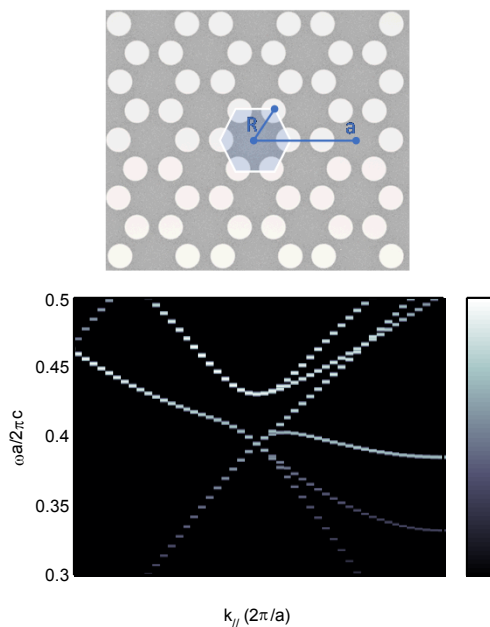
Modified honeycomb lattice of hexagonal cylindrical dielectric rods

Photonic Bandstructures for Modified Honeycomb Lattices

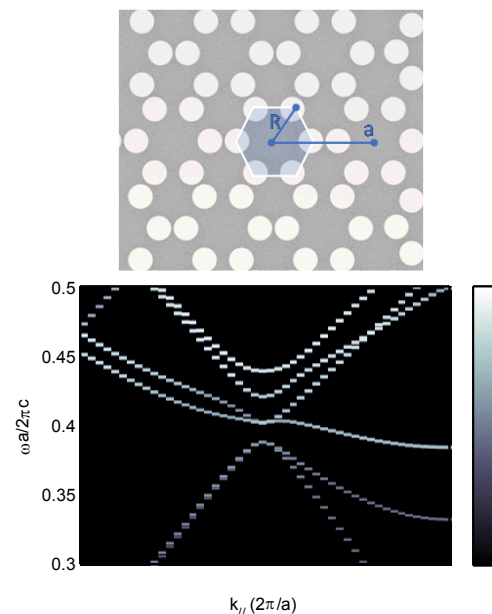
☐ Holes in dielectric design can be useful for optical frequency photonics applications



Trivial ($a/R = 3.2$)



Honeycomb ($a/R = 3.0$)

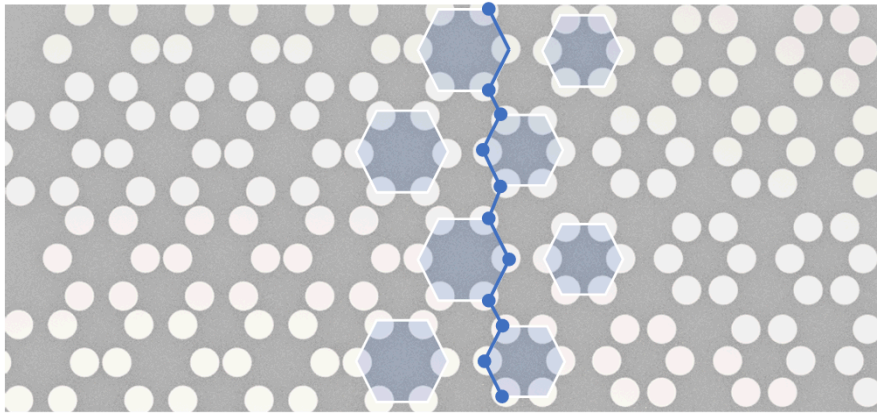


Topological ($a/R = 2.9$)

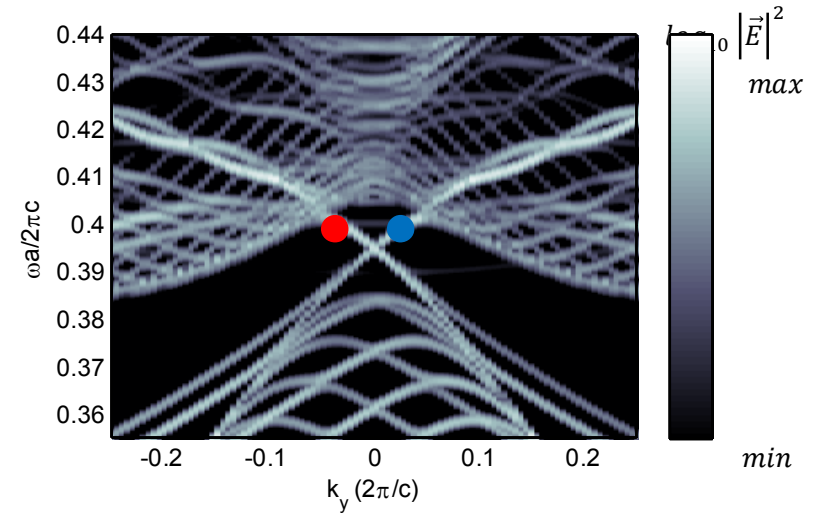
($r/a \sim 0.12$)

Calculated with FDTD
(Lumerical[®])

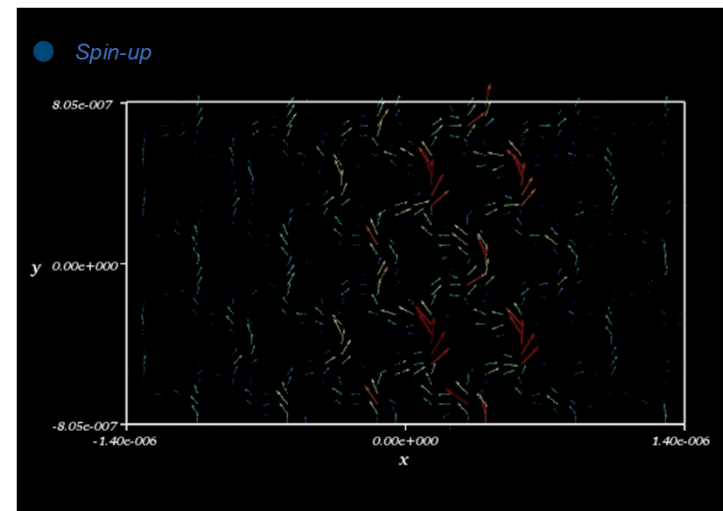
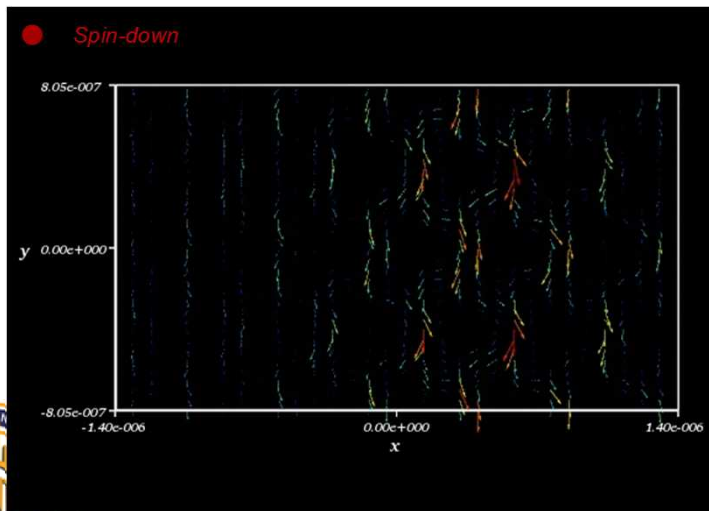
Band structure for Topological/Trivial Zig-zag Interface



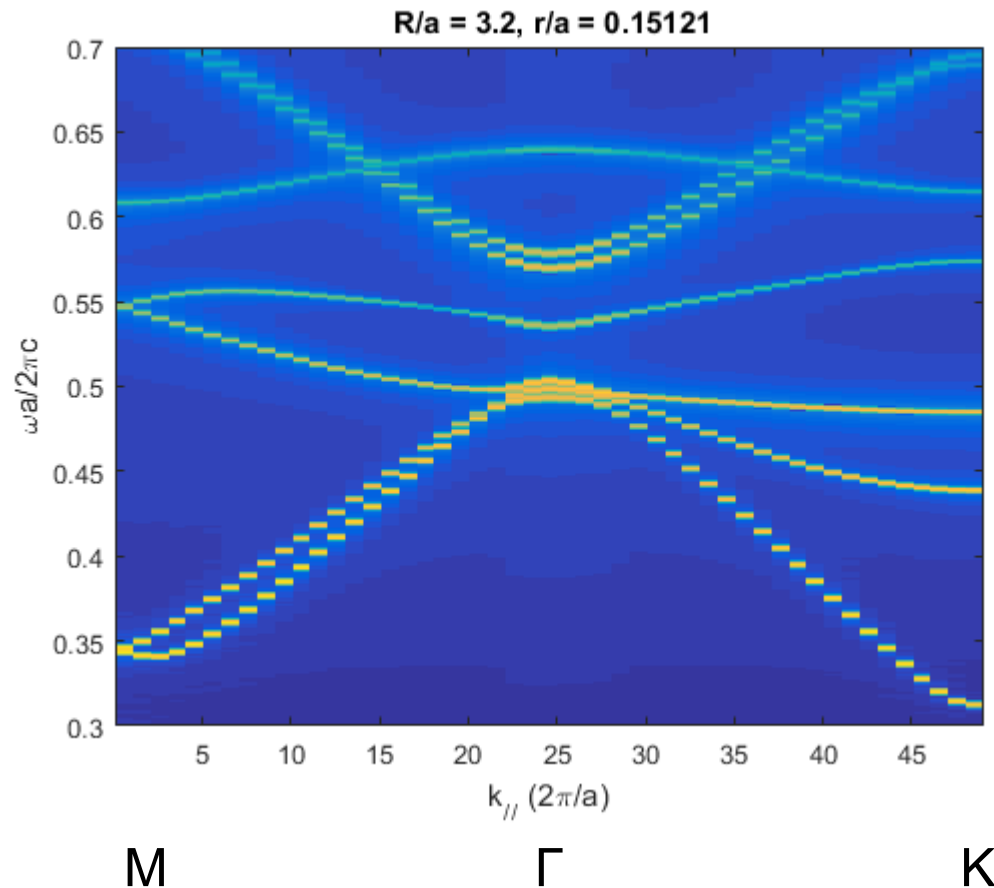
$(r/a \sim 0.12)$



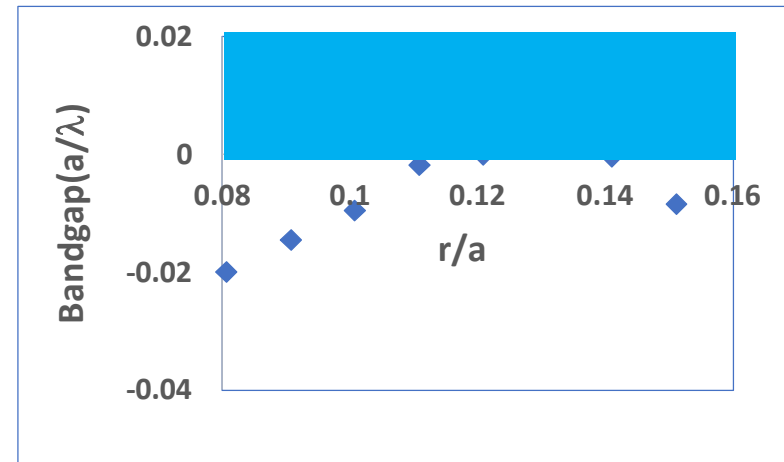
- Crossing unidirectional edge states are observed



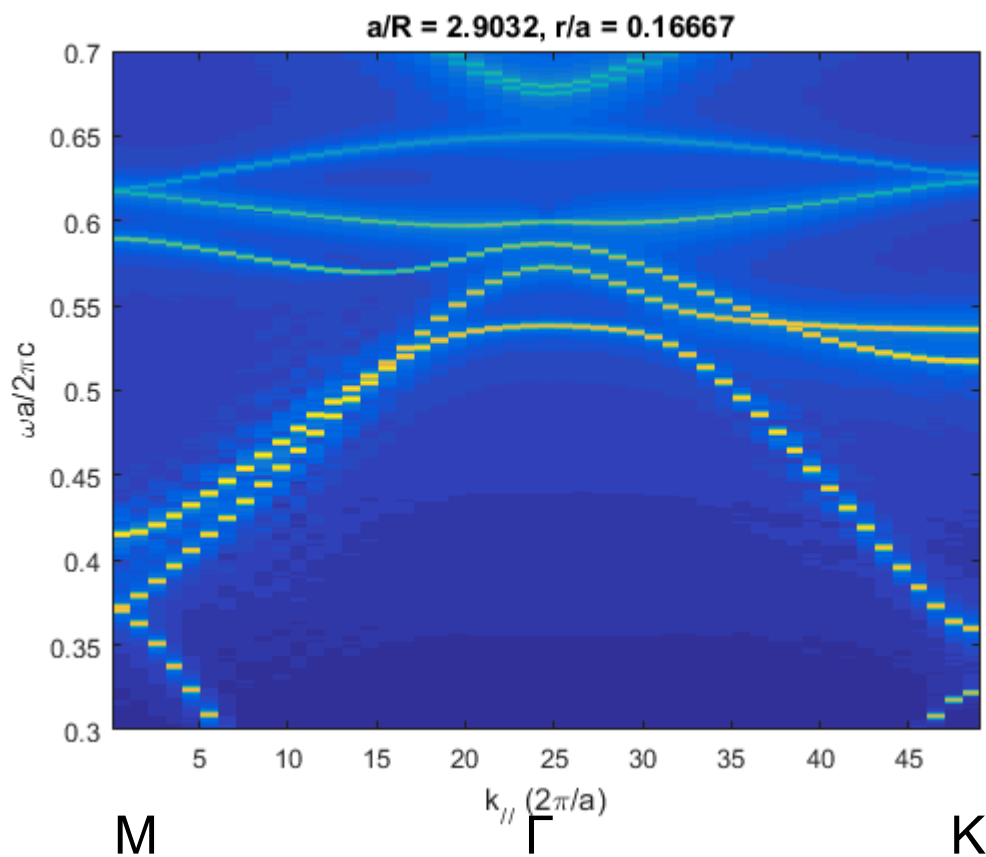
Band structure for Trivial Lattice ($a/R = 3.2$) varying r/a



~ 0.0025 gap

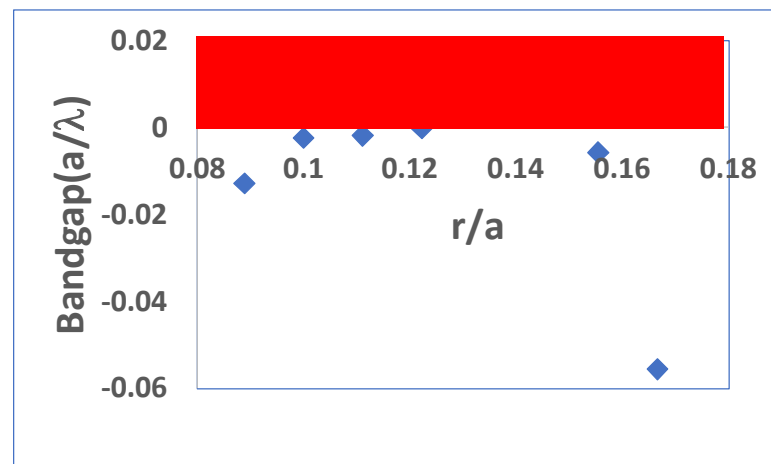


Band structure for Topological Lattice ($a/R < 2.9$) varying r/a

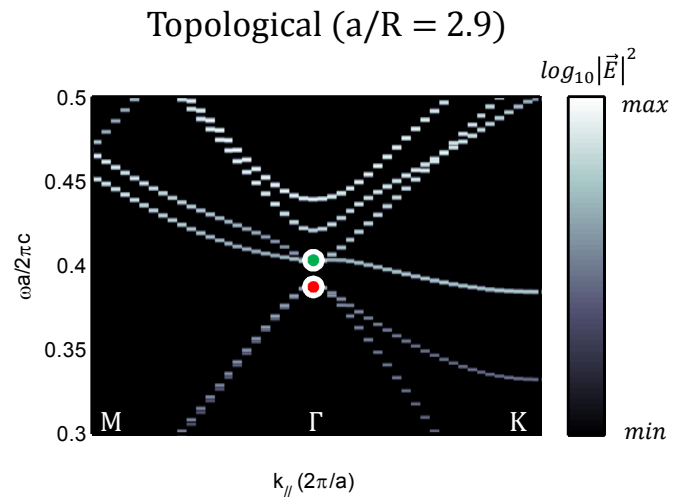
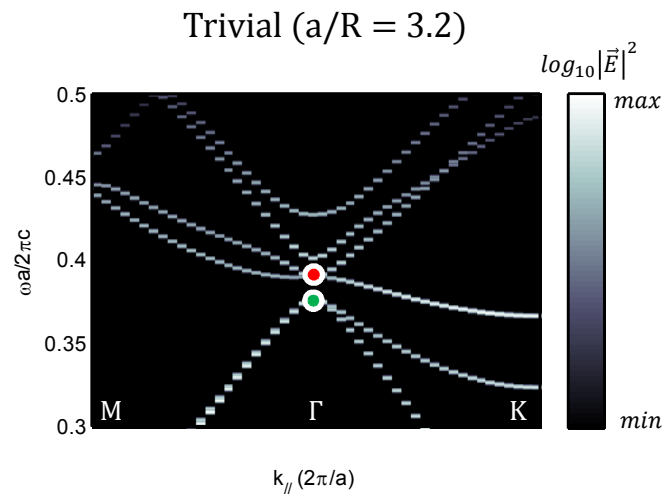


~ 0.007 gap at ~ 0.46

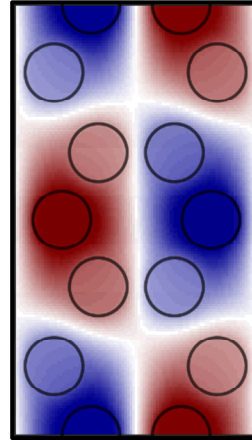
~ 23 nm @ $\lambda = 1550$ nm



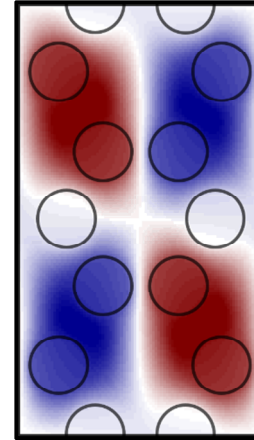
Field Distribution



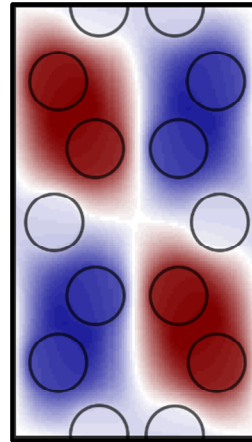
p_x



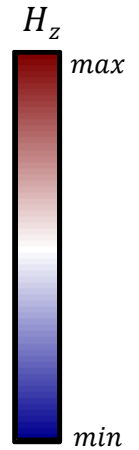
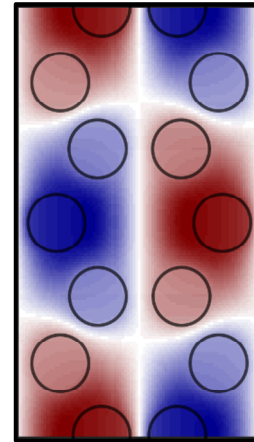
d_{xy}



d_{xy}

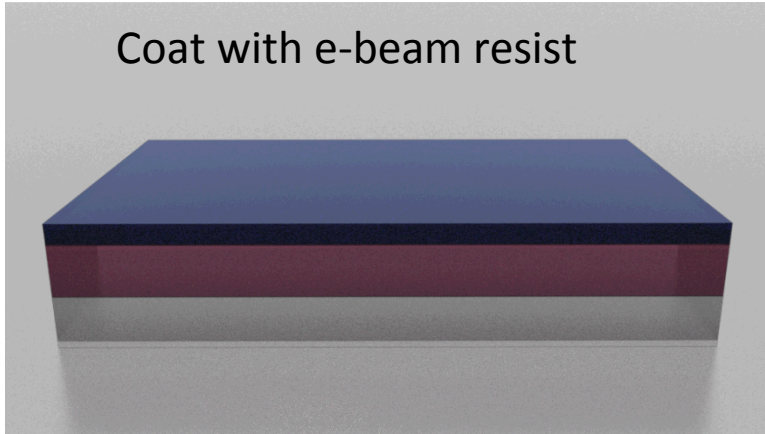


p_x

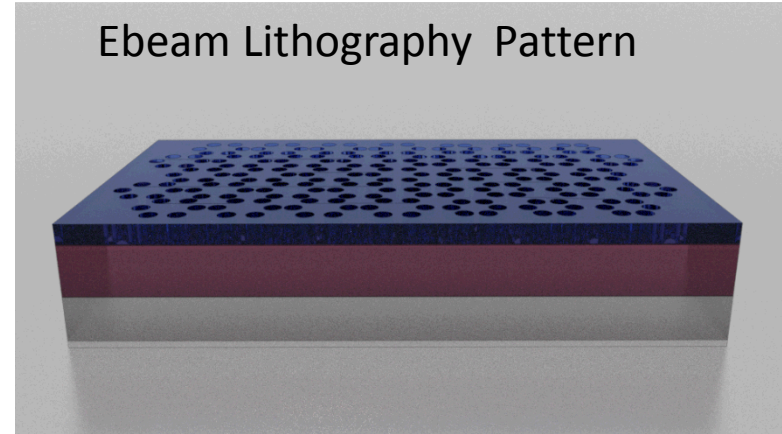


Fabrication on Silicon on Insulator (SOI) - Membrane

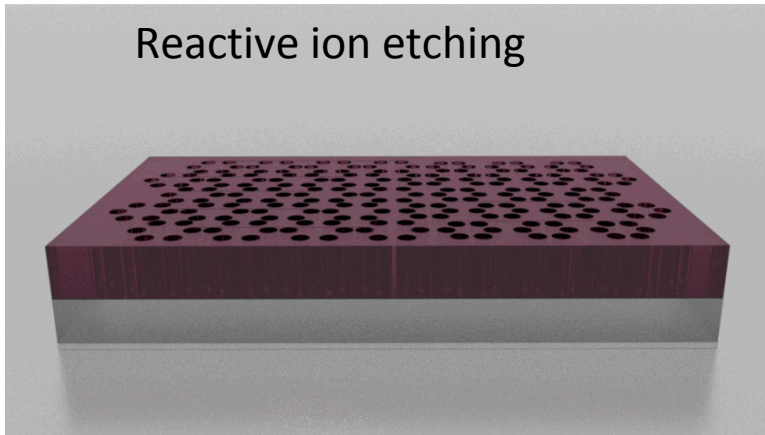
Coat with e-beam resist



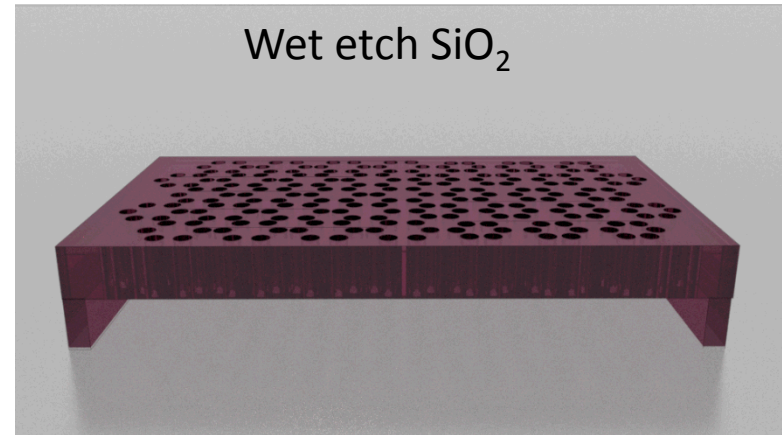
Ebeam Lithography Pattern



Reactive ion etching

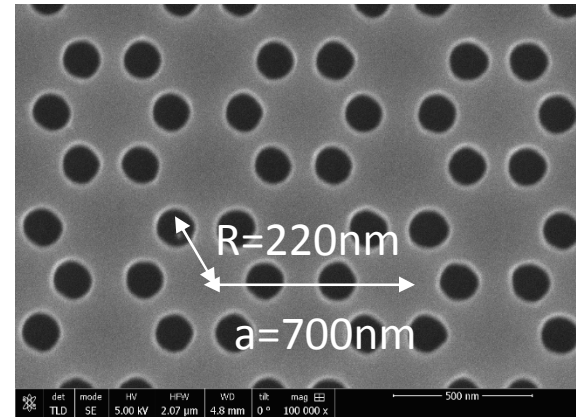
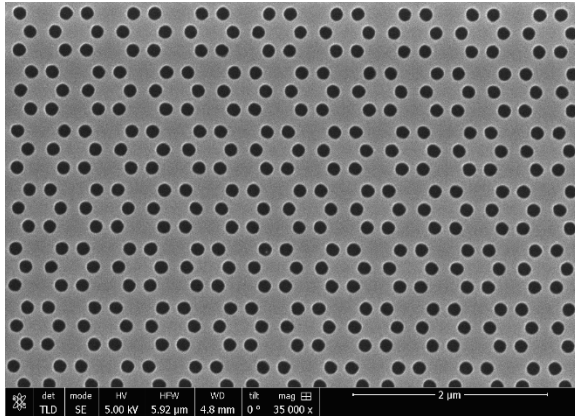


Wet etch SiO₂



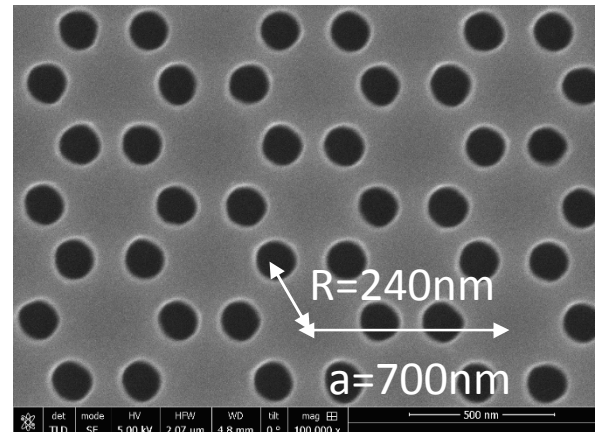
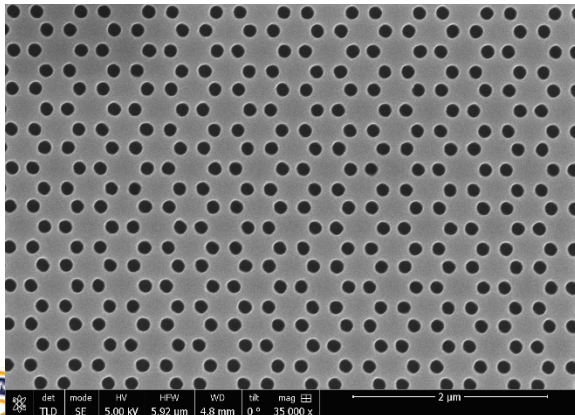
Fabrication on Silicon on Insulator (SOI) - Membrane

Trivial/Compressed Structure



$$a/R = 3.18$$

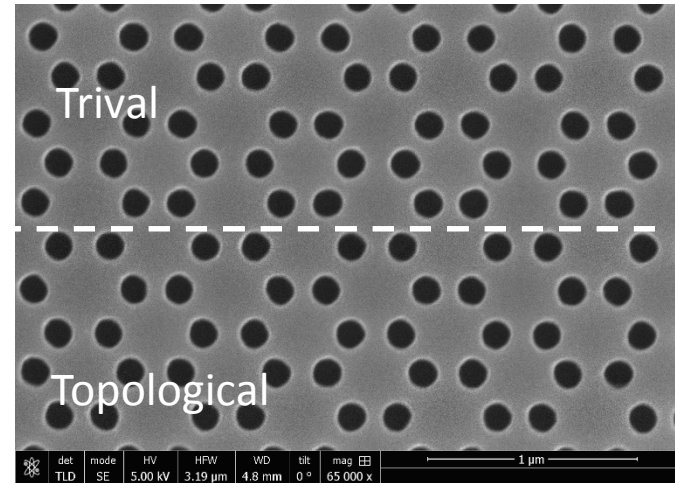
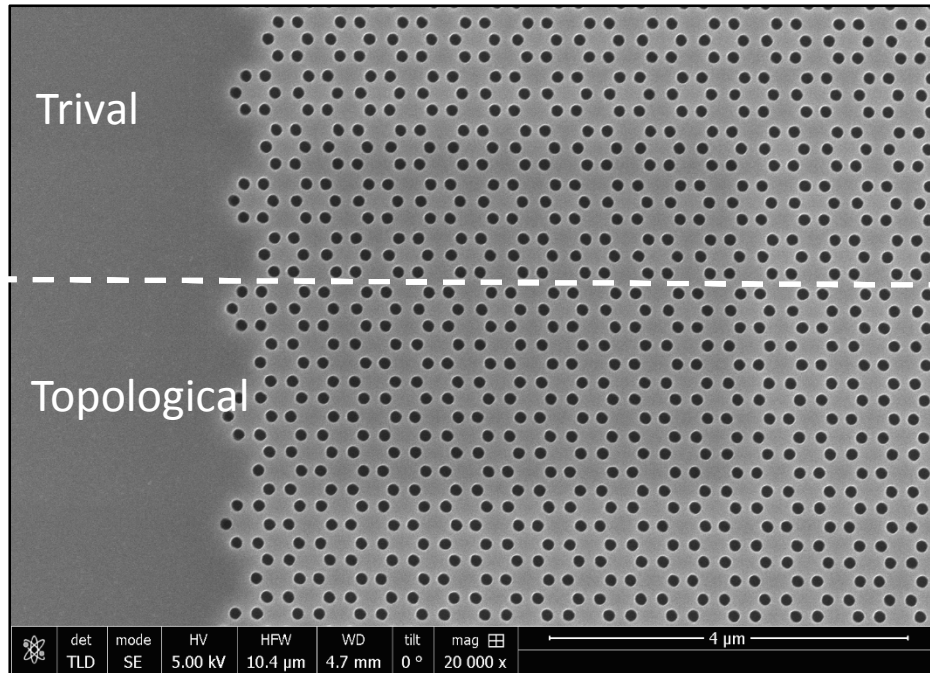
Topological/Expanded Structure



$$a/R = 2.9$$

Fabrication on Silicon on Insulator (SOI) - Membrane

Topological/Trivial Interface structure

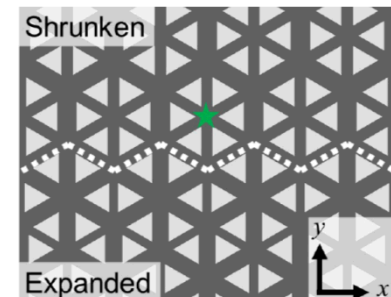


Alternate design ...

arXiv:1605.08822v1

Two-Dimensionally Confined Topological Edge States in Photonic Crystals

Sabyasachi Barik^{1,2}, Hirokazu Miyake², Wade DeGottardi², Edo Waks^{2,3}, Mohammad Hafezi^{2,3,4}



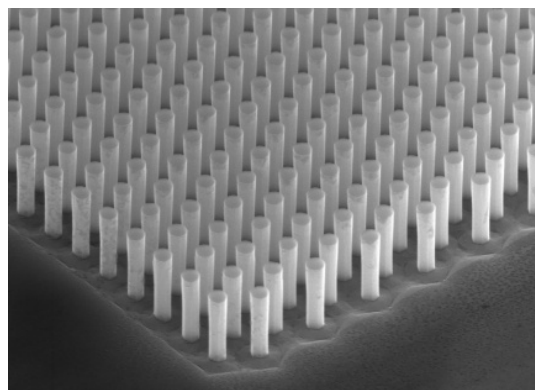
Fabrication could be challenging ...



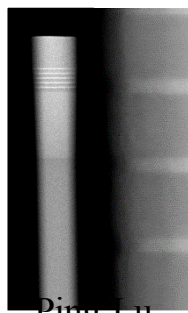
Topological structure in active material systems

PhC nanrod array have shown excellent light emission behavior

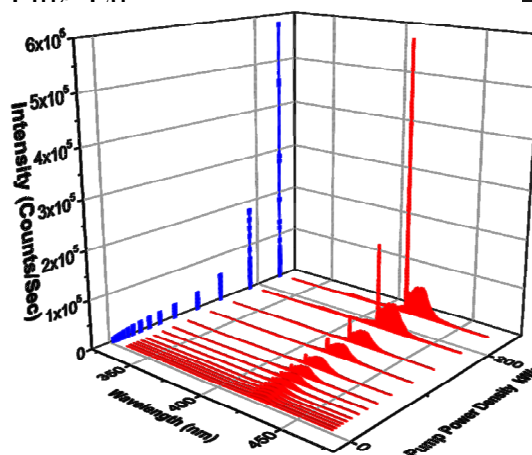
Demonstration of Lasing from PhC Array



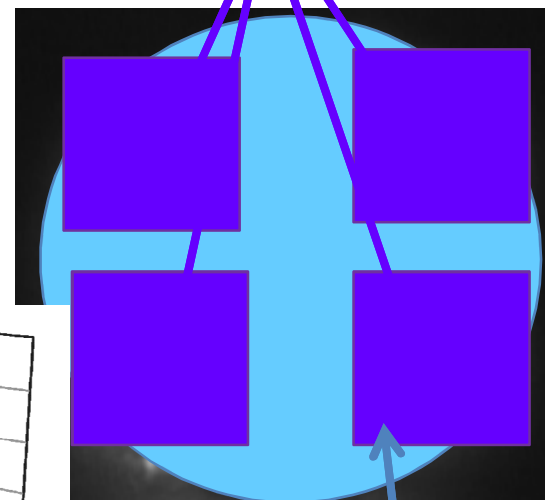
Fabricated by using a top down approach from a planar GaN with InGaN Multiple quantum wells



Pinned



Photonic Crystal Laser Pixels



Pump Spot

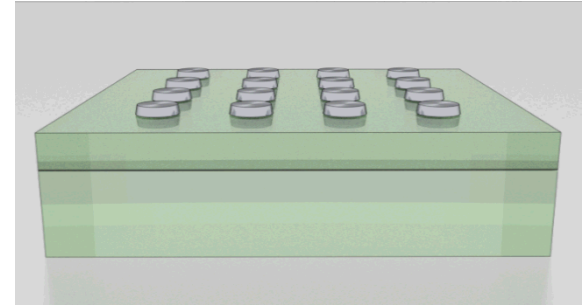
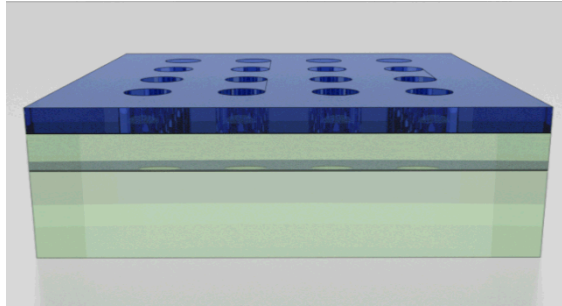
J. B. Wright et,al., Sci. Rep. **3**, 2982 (2013).

Light sources with interesting angular momentum properties ?

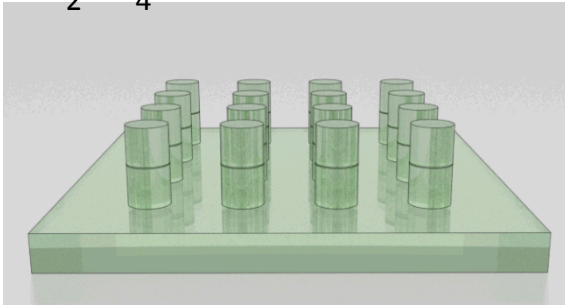
Fabrication procedure in GaN

Ni evaporation and lift-off

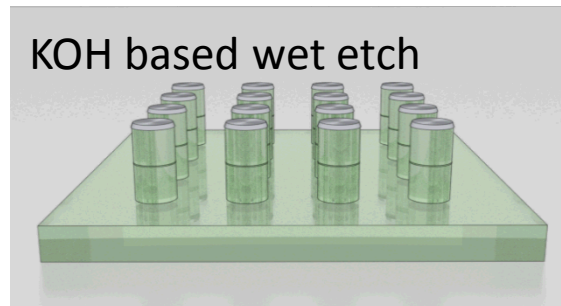
EBL pattern in
PMMA



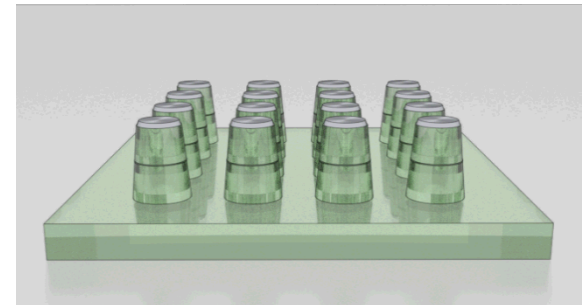
H_2SO_4 -based Ni removal



KOH based wet etch



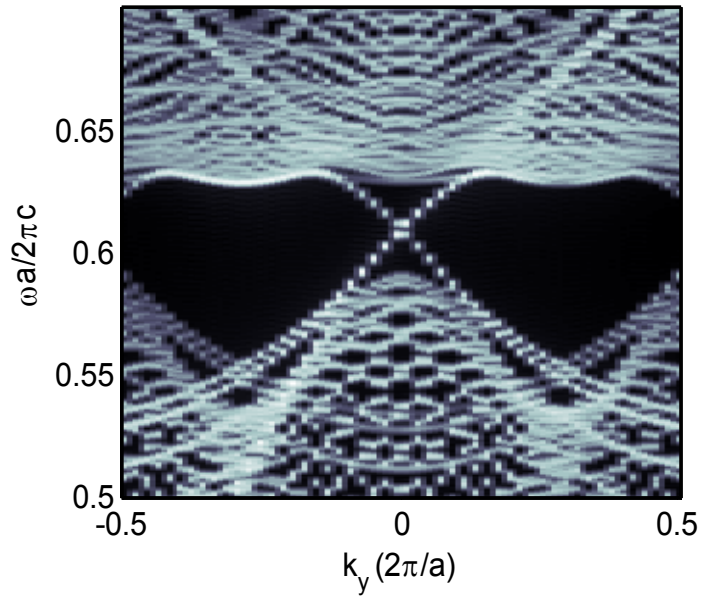
Cl_2 based dry etch



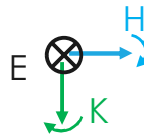
Topological edge state in honeycomb lattice structure in III-Nitride

Modeling

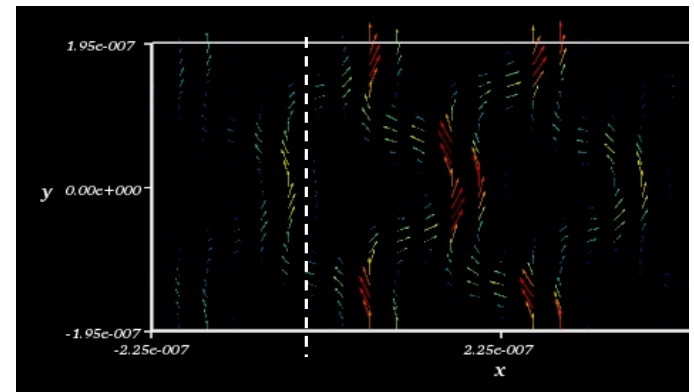
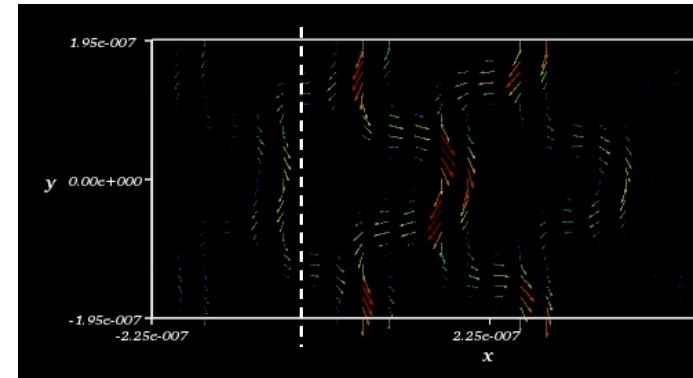
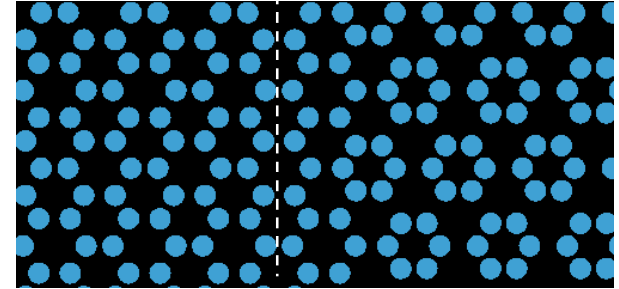
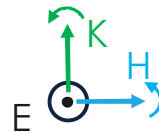
Band Structure



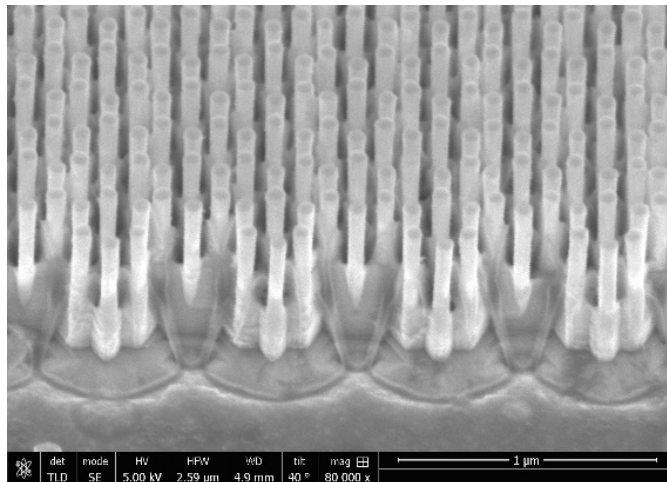
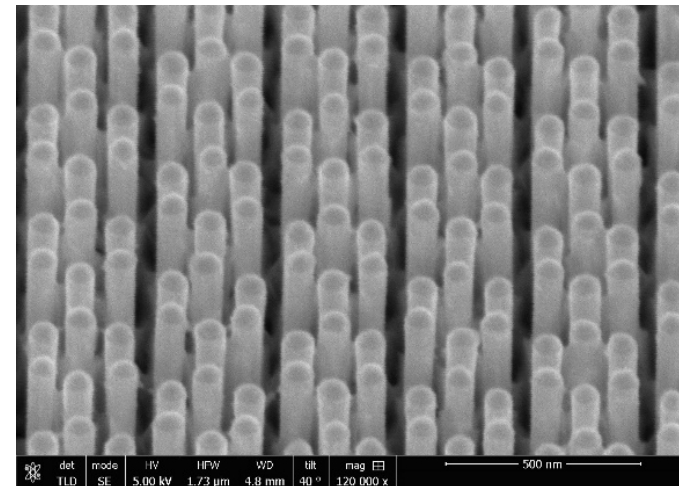
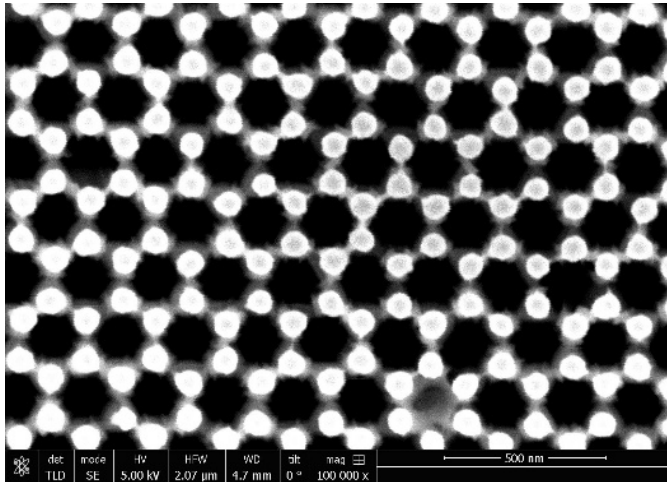
Spin-down state
 $a/\lambda = 0.618$



Spin-up state
 $a/\lambda = 0.60$



Topological/Trivial lattice interface structure in III-Nitride

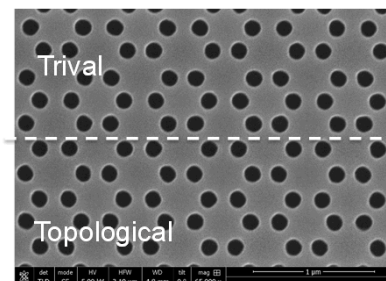
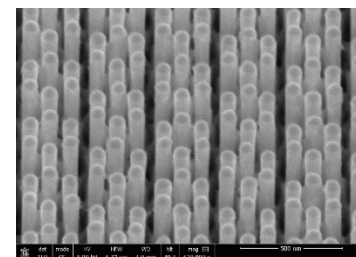
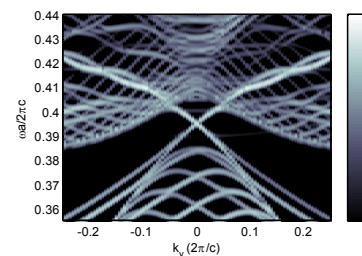


Ongoing ...

- ☐ Main challenges
 - ☐ Deeper etching
 - ☐ Source polarization

Summary and Future directions

- Hole array honey comb lattice structure for photonic pseudo spin
- Fabrication in III-nitride
- Fabrication in Silicon/SOI



Next...

- Optimize design and fab – Si and III-N
- Optical measurement to demonstrate Topological behavior

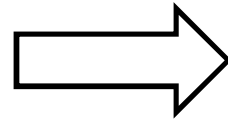
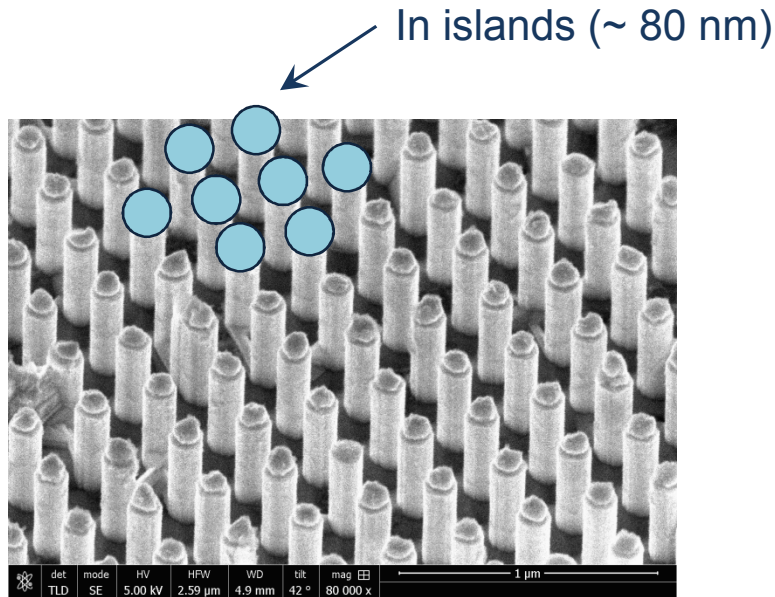


Thank you for your attention!

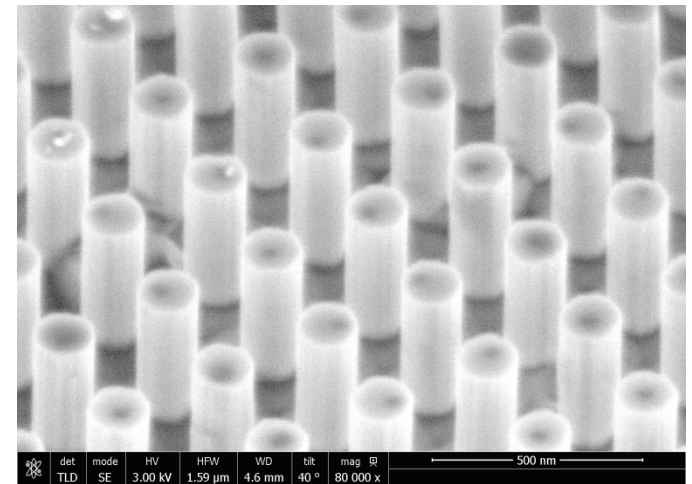
Extras

Removal of Indium Hard Mask

In islands remain after dry Cl etch → degrade optical performance



Remove In (1:2 H₂SO₄, DI H₂O)



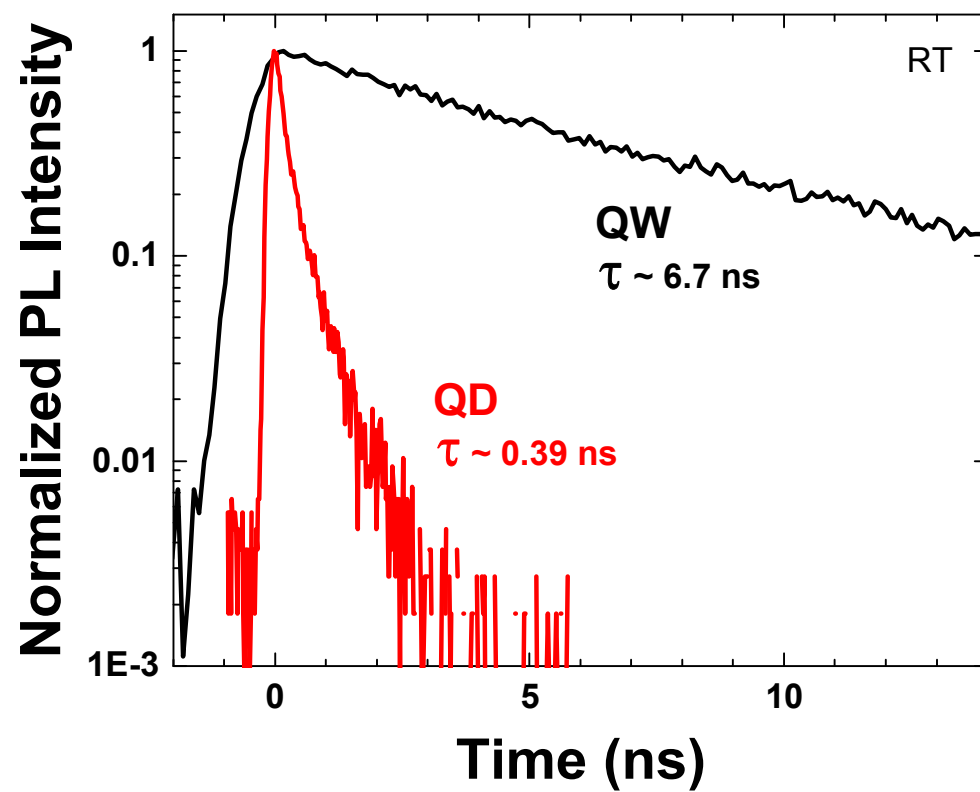
Why H₂SO₄?

Sulfuric acid can selectively etch Ni and avoid GaN

Ni removed relatively quickly (~ three minutes)

Time-resolved PL data from InGaN QDs

Capped InGaN QW



TRPL data:

- 405 nm pump (~ 2 ps, pulsed)
- Resonant pumping into InGaN
- Room temperature TRPL data
- Hamamatsu streak camera data
- 17X change in PL lifetime
- Lifetime is expected to be much shorter for QDs
- Shows that we have fundamentally changed the InGaN material
- QW $\rightarrow$ QDs

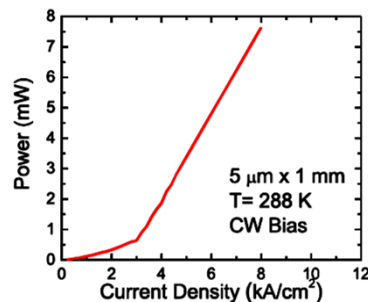
Motivation for InGaN Quantum Dot Emitters

- **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:

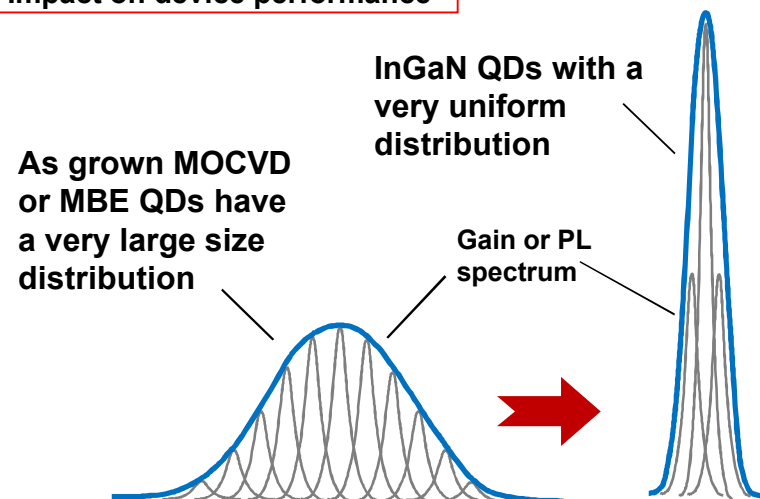
- **University of Michigan**
- Electrically injected
- 630 nm
- $T_o = 236\text{K}$

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



Monodisperse QD Distributions

Impact on device performance



- Advantages to this approach
 - InGaN QDs can operate at high temperatures
 - Si detectors work well in the blue/green
 - Free space data links: Reduce the size of optical telescopes
 - Plastic optical fiber at blue/green wavelengths
 - Deterministic placement of InGaN QDs
 - Leverage expertise in III-nitrides and photonic crystals