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III-Nitride Nanophotonics

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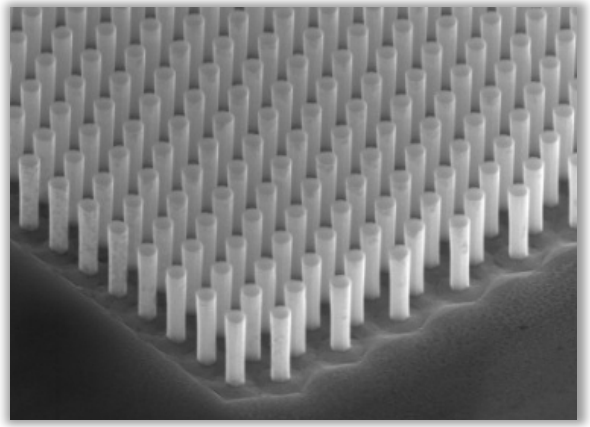
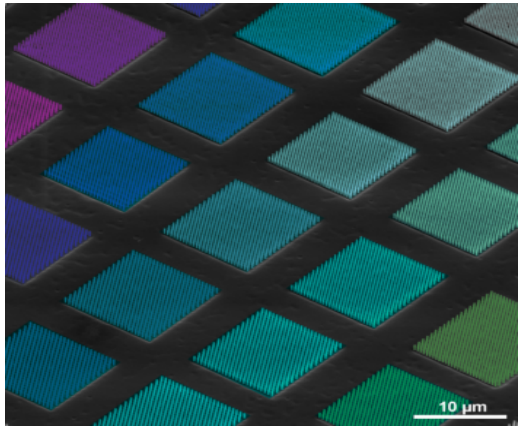
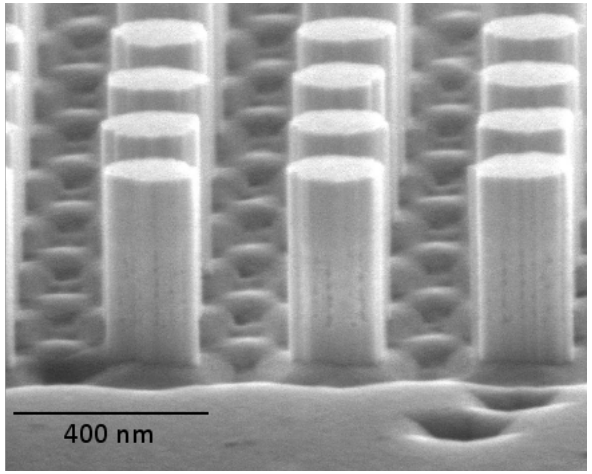
Semiconductor Materials and Device Sciences,
Sandia National Laboratories, Albuquerque, NM

OSE Seminar
UNM, December 9, 2021







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Synopsis

Ubiquitous presence of III-nitride based solid state lighting has opened up III-nitrides as important materials for visible and UV nanophotonics. Nanophotonic architectures such as photonic crystals and metamaterials/metasurfaces have become key players in modern photonics. They have enabled unprecedented capabilities combined with great versatility to control various properties of light -propagation, polarization, emission and photon statistics. Unique materials processing challenges posed by III-nitride materials motivates us to explore alternate techniques for nanostructure fabrication compared to Si and III-Vs. In this talk, I will present some of the approaches and results of III-N nanophotonics research based on photonic crystals and metamaterials performed at Sandia.

Collaborators

Sandia

- Nick Karl
- Keshab Sapkota
- George Wang
- Igal Brener
- Art Fischer
- Dan Koleske
- Duke Anderson
- Jeremy Wright
- Jeff Tsao

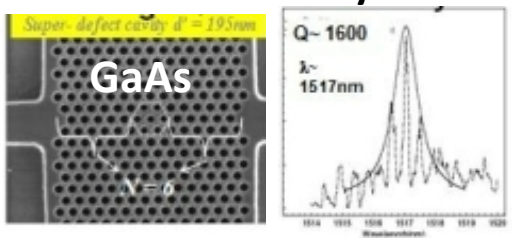
UNM

- Daniel Feezell
- Zachary Meinelt

Nanophotonics Activity

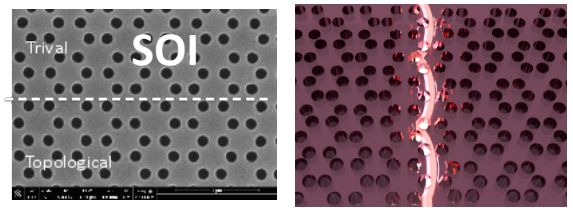
Integrated Photonics, Nanoscale lasing, Emission control, Solid State lighting, Energy conversion, Non-classical light sources, Subwavelength light control, Detection, Sensing , Nanocircuitry

2D PhC cavity



Subramania, G., et. al., J. M. *App. PhyS. Lett.* **83**, 4491(2003).

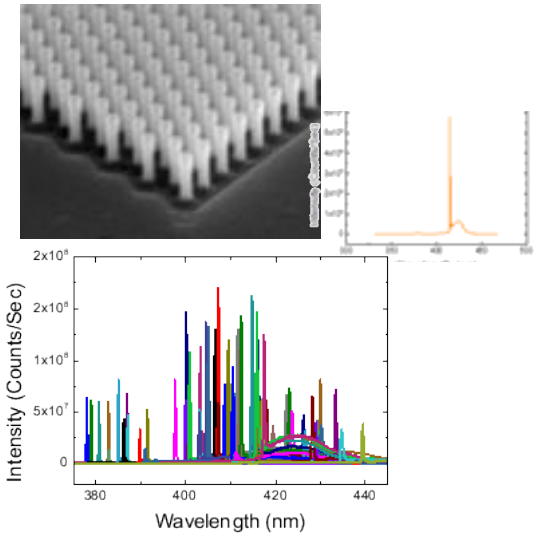
Topological Photonics



P. D. Anderson and G.Subramania, Optics Express **25** , 23293 (2017).

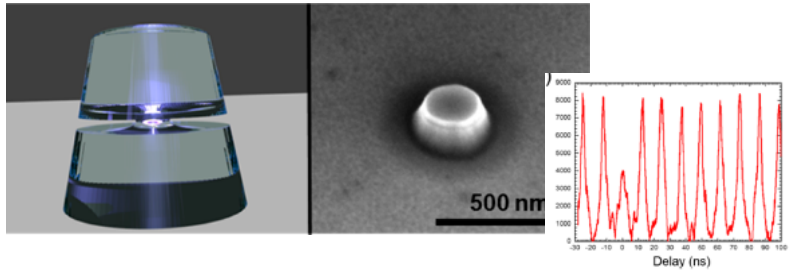
2D Photonic Nanostructures

GaN PhC multicolor lasers



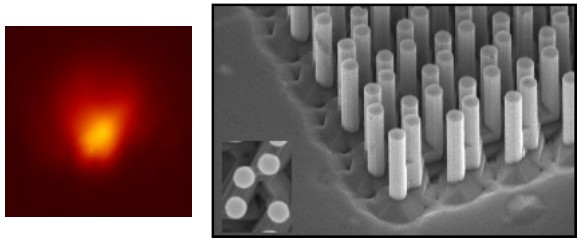
Wright, J. B. *et al. Sci. Rep.* **3**, 2982(2013)

GaN QD for single photon sources



Fischer, A. J. et. al, . *ACS Phot.* **4**, 2165, (2017).

GaN quasi-periodic



Anderson, P. D. e.t. al.. *Opt. Mat. Exp.* **7**, 3634-3642, (2017).

Nanophotonics Activity

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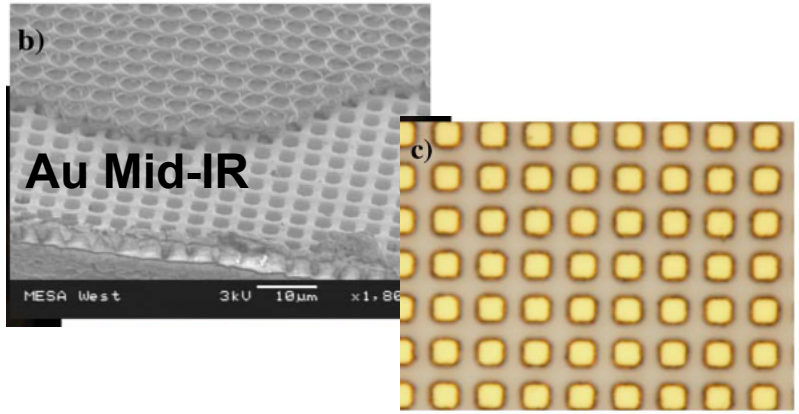
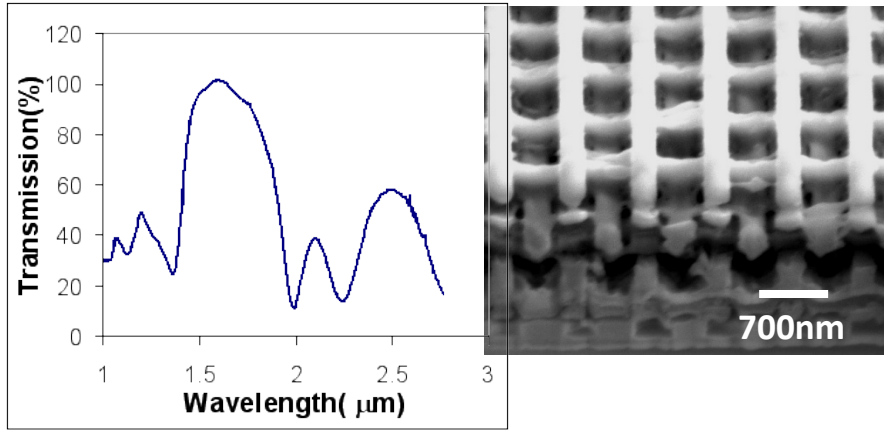
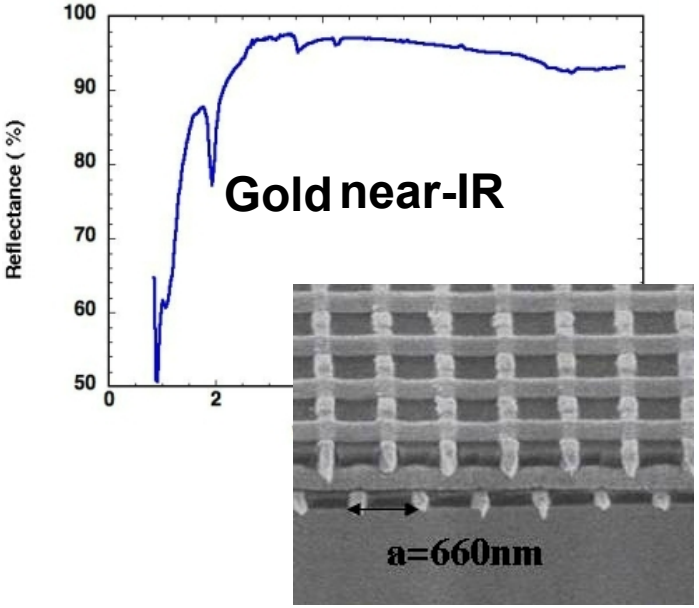


Si near-IR



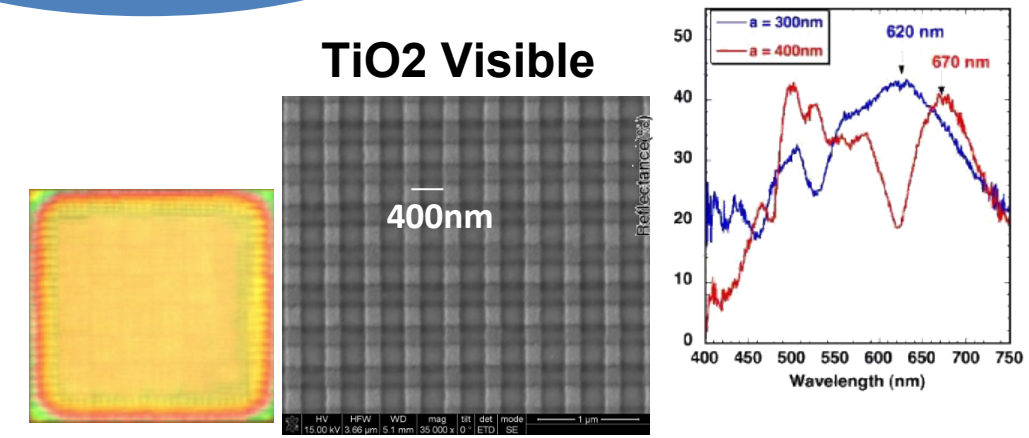
G. Subramania and S. Y. Lin, Applied Physics Letters 85 (21), 5037 (2004)..

3D Photonic Crystals



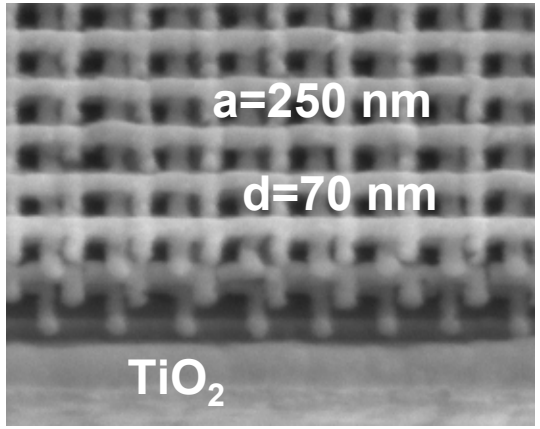
Subramania, G.; Rivera, J. M., Organic and Nanocomposite Optical Materials 2005, MRS proc. **846**, 321

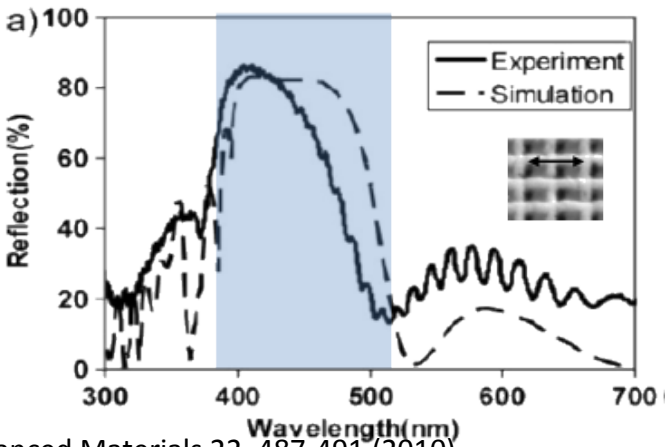
TiO2 Visible



G. Subramania, Y-J. Lee, I. Brener, T.S. Luk, and P.G. Clem, Optics Express 15 (20), 13049 (2007).

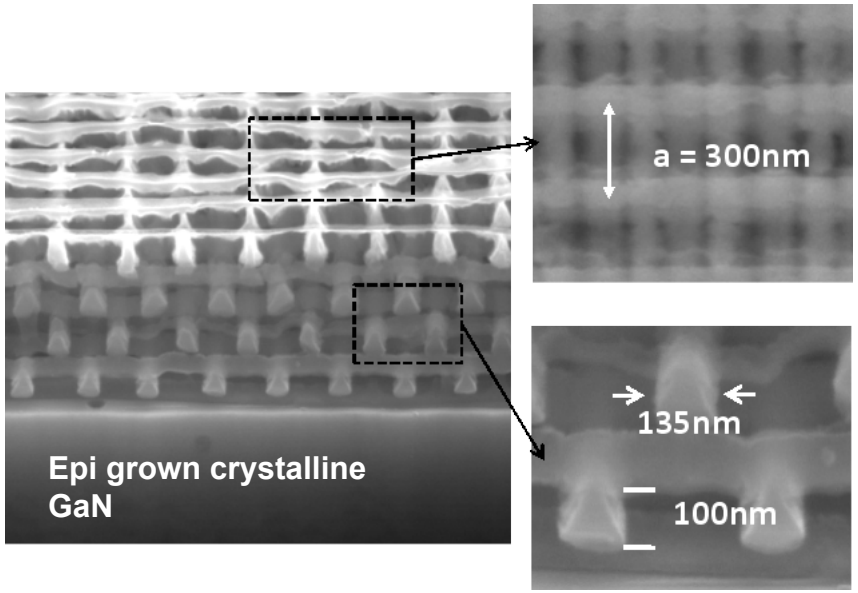
Nanophotonics Activity

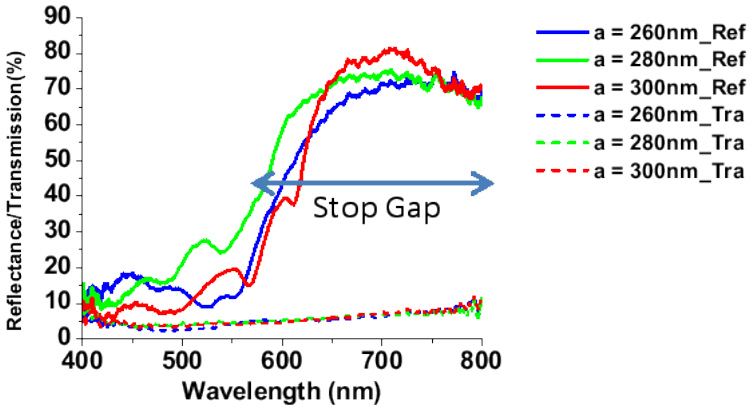




G. Subramania, Y.-J. Lee, A. J. Fischer, and D. D. Koleske, Advanced Materials 22, 487-491 (2010)

3D Photonic Crystals





G. Subramania, Q.Mi Li, Y-J Lee, J. J. Figiel, G. T. Wang, and A. J. Fischer, Nano Lett. 11 4591 (2011).

Outline

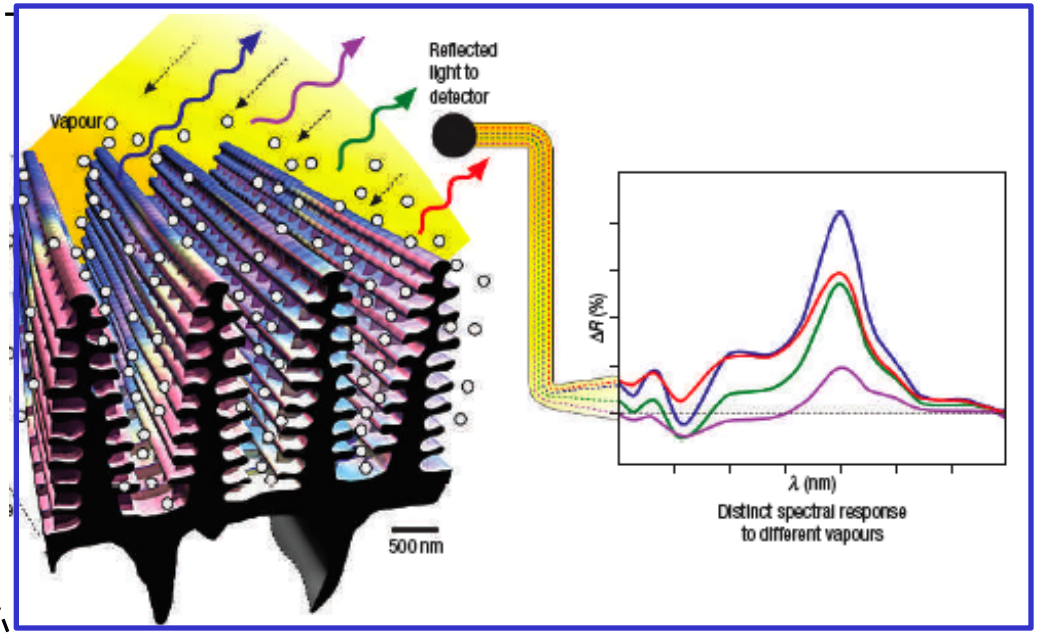
- Introduction on light control with nanostructuring
- Lasing in III-N Nanowire 2D Photonic Crystals
  - Photonic band structure, fabrication, emission profile
- III-Nitrides for Metasurfaces
  - Forward scattered transmission, cladding for substrate isolation
- Quantum Dots for Single Photon Sources (time permitting)

Contolling Light via Nanostructuring : in Nature

- **Color response highly sensitive to different vapors**

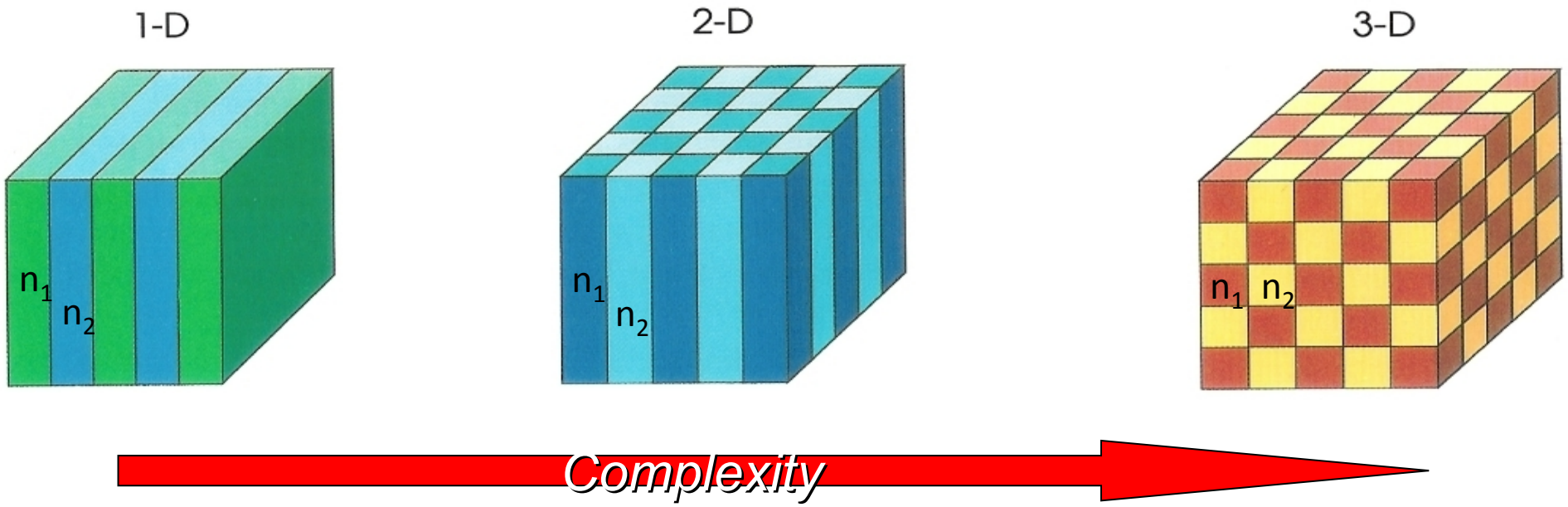
Morpho Butterfly

(M. Sulkowskyi)



* R.A. Potyrailo et. al. , Nature Photonics , **1**, 123(2007).

Photonic Crystals: Nanostructured Electromagnetic Environment



Control of light propagation

- Guiding, bending and splitting
- Negative refraction
- Self-collimation
- Localization
- Slow light
- Cloaking

Control of light emission

- Spontanteous emission enhancement
- Strong-coupling (Photon – Atom Bound states, Non-Markovian emission process)
- Non-classical light sources

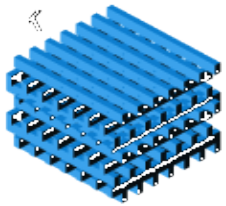
Reference: "Photonic crystals: Molding the flow of light", J.D. Joannopoulos, R.D. Meade, J. Winn, Princeton Univ.Press, NJ(1995)

Spontaneous Emission Control using PC

Sandia National Laboratories

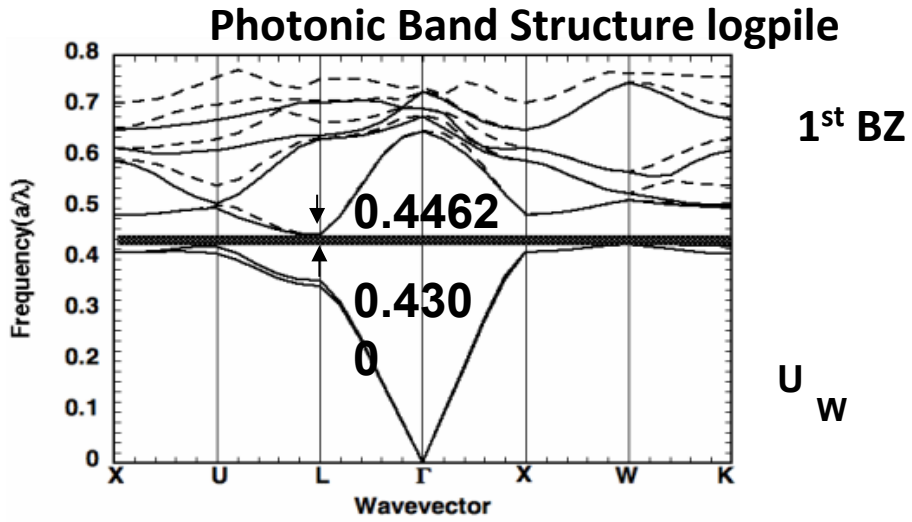
Radiative rate of an emitting dipole in an EM field (Fermi's Golden Rule)

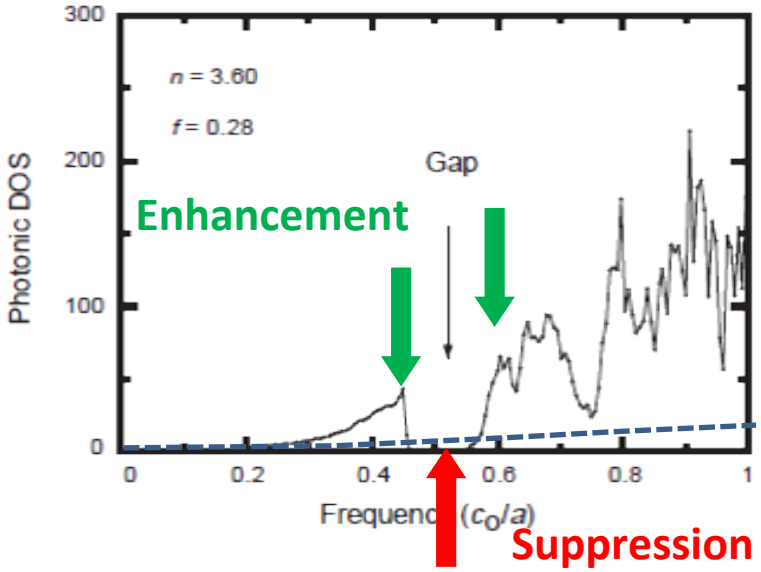
$$\Gamma_r(\omega) = \frac{\pi\omega\mu^2}{3\varepsilon_0 \square}\rho(\omega)$$



Photonic Density of States (PDOS)

$$\rho_f(\omega) = \frac{\omega^2}{\pi^2 c^3}$$ ← in free space





Radiative rate modification

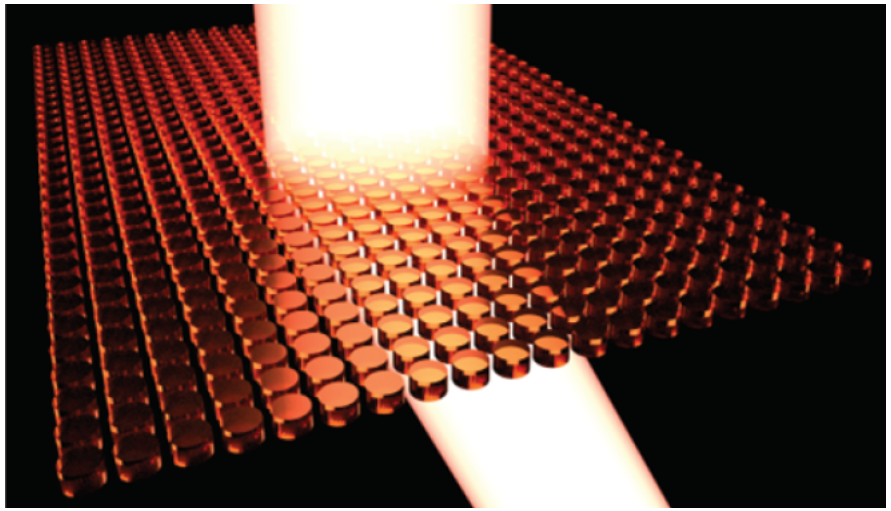
$$\frac{\Gamma_{r\_PC}(\omega)}{\Gamma_{r\_free}(\omega)} = \frac{\rho_{PC}(\omega)}{\rho_f(\omega)}$$

Local Photonic Density of States (LDOS)

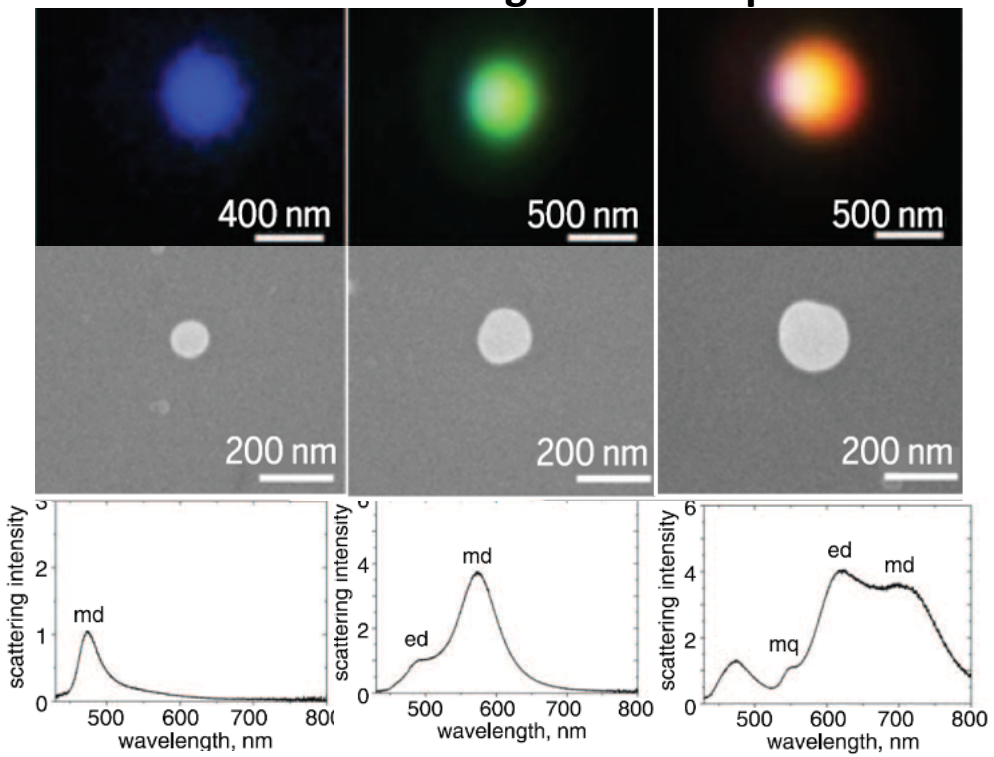
$$\rho_L(\boldsymbol{r},\omega) = \sum_n \int_{1stBZ} d^3k \left|\overline{\mu}\cdot \boldsymbol{E}_{n,k}(\boldsymbol{r})\right|^2 \delta(\omega^2 - \omega_{n,k}^2)$$

Huygen's Metasurfaces

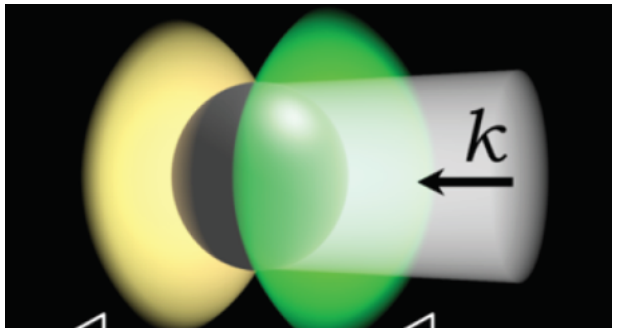
Scatterers perpendicular to light propagation



Electric and Magnetic Multipoles

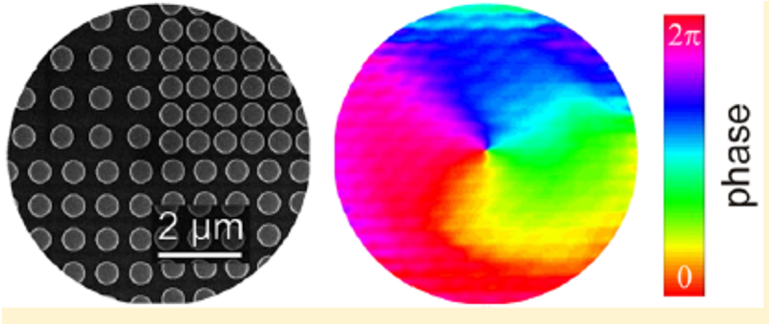


High efficiency forward scattering occurs when ED and MD align



A.Kuznetsov et. al. Science **354** (6314), aag2472 (2016).

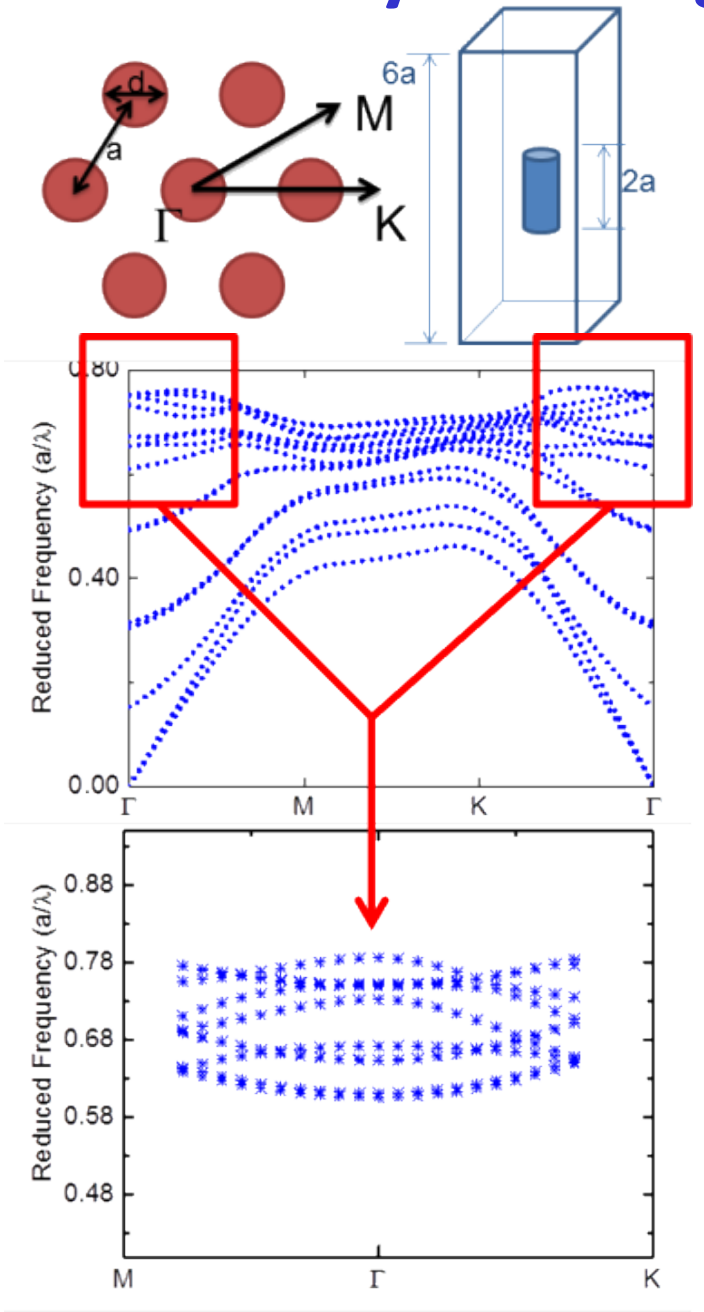
Optical Wavefront Control



Katie E. Chong et. al. Nano Lett. **15** (8), 5369 (2015)

Lasing in III-N Nanowire2D Photonic Crystals

Vertically emitting photonic crystal lasers - Theory

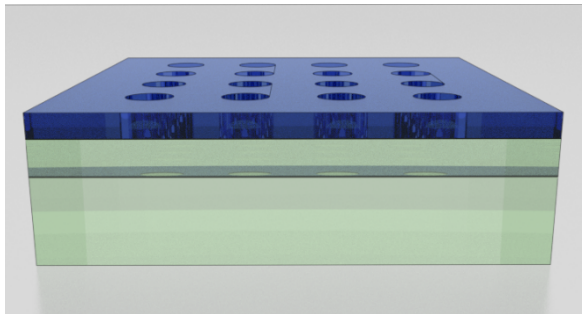


- ***Low lasing threshold***
  - ***Increase interaction of light with the gain region***
  - ***Enabled by 'Low group velocity modes' in photonic crystal****
- ***Vertical Emission***
  - ***At higher bands there are low group velocity modes near the Gamma point***
  - ***Near the Gamma point the in-plane wave vectors are small resulting in near-normal emission***
- ***Wavelength Tunability***
  - ***Achieved through lattice constant and nanowire diameter variation***

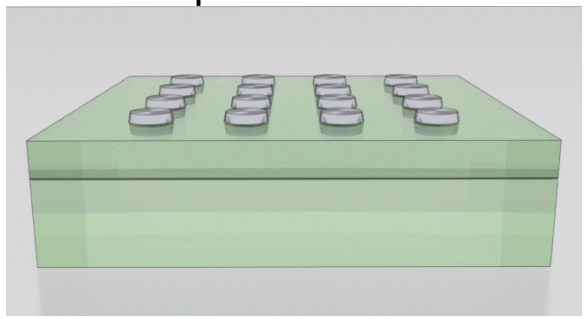
*Sakoda, K. *Optical Properties of Photonic Crystals*. (Springer-Verlag, 2001).

Fabrication of III-N nanowire laser array

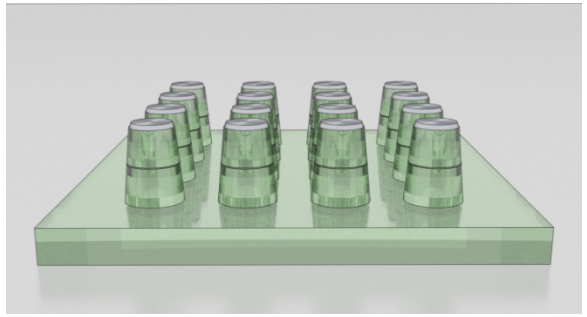
EBL pattern in PMMA



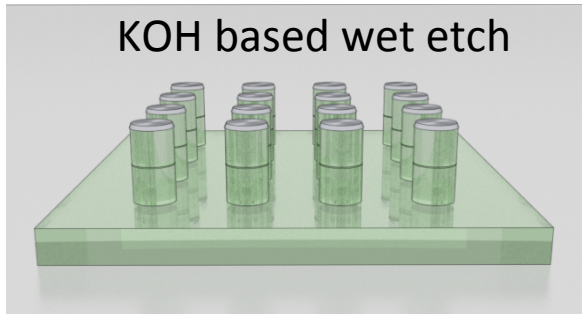
Ni evaporation and lift-off

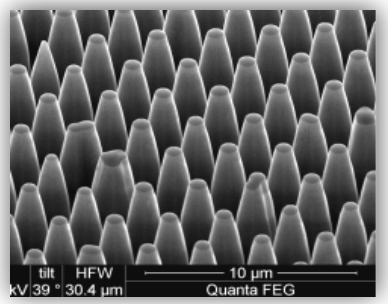


Cl2 based dry etch

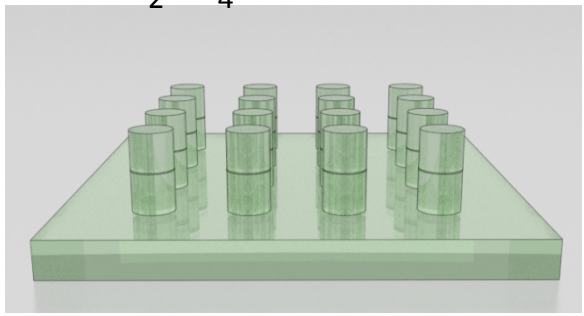


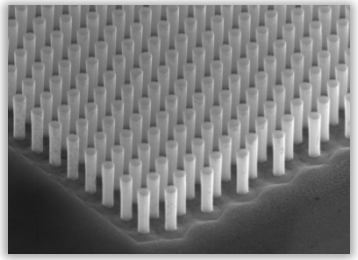
KOH based wet etch

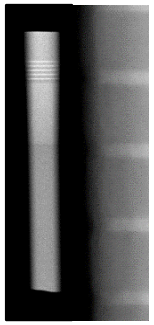




H_2SO_4–based Ni removal



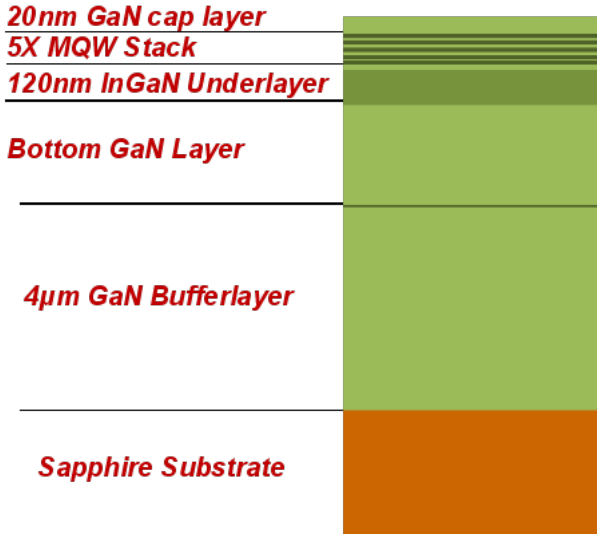




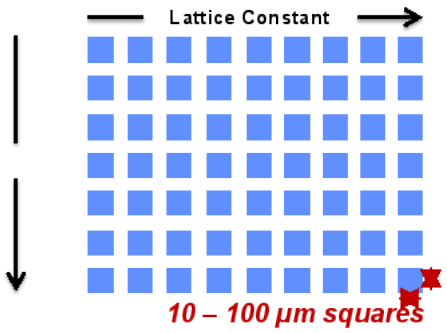
Wright, J. B. *et al.* Multi-Colour Nanowire Photonic Crystal Laser Pixels. *Sci. Rep.* **3**, 2982,(2013)

Fabrication of III-N nanowire laser array

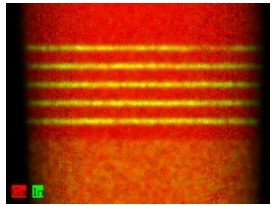
Growth of III-N active material

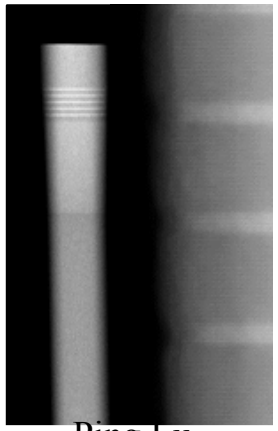


Patterning of 2DPC using e-beam lithography



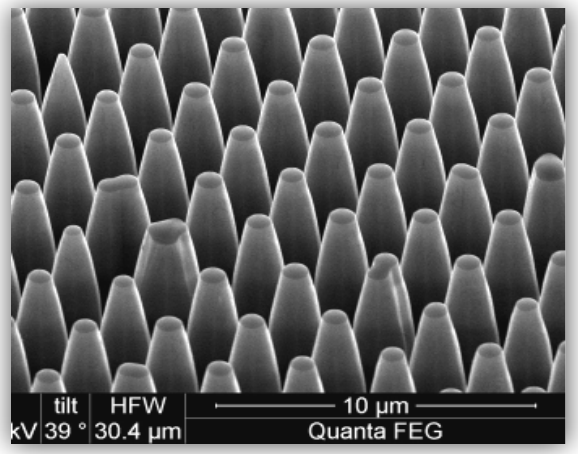
TEM images

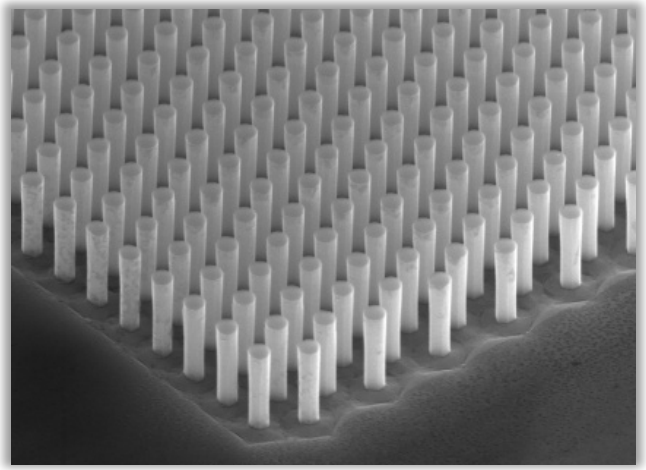




Ping Lu, Sandia

Inductively coupled plasma dry etch





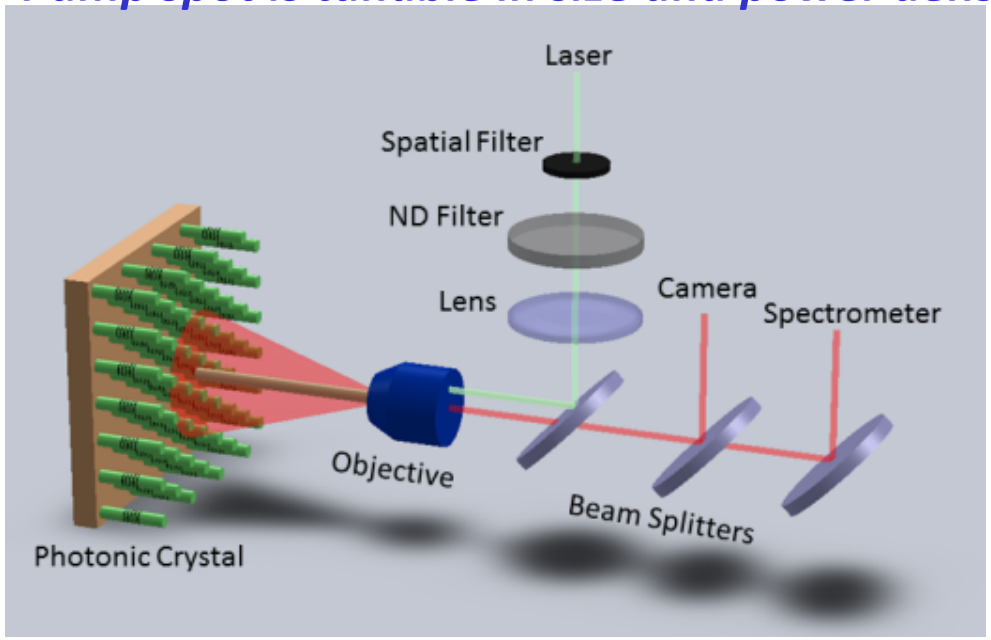
Wet etch using KOH process

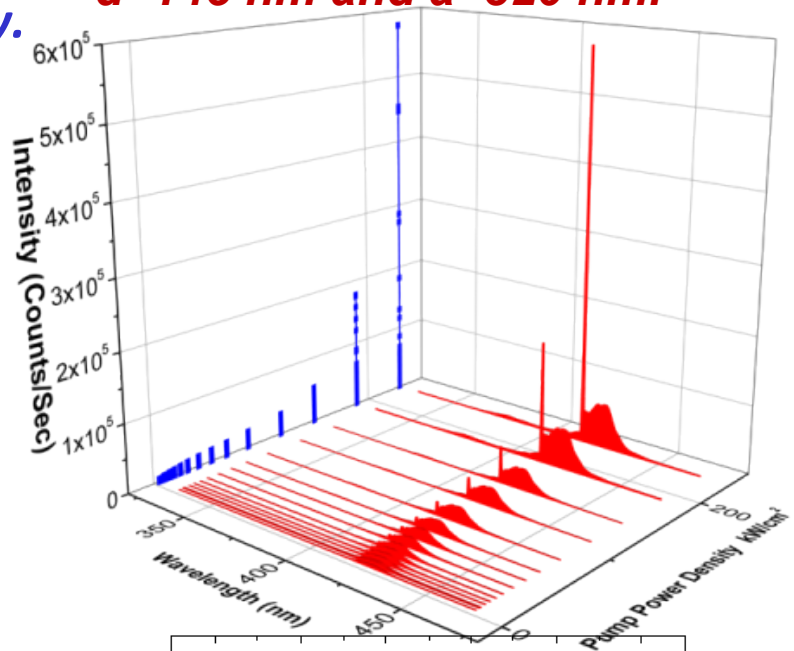
Wright, J. B. *et al.* Multi-Colour Nanowire Photonic Crystal Laser Pixels. *Sci. Rep.* **3**, 2982,(2013)

Optical response – low threshold lasing

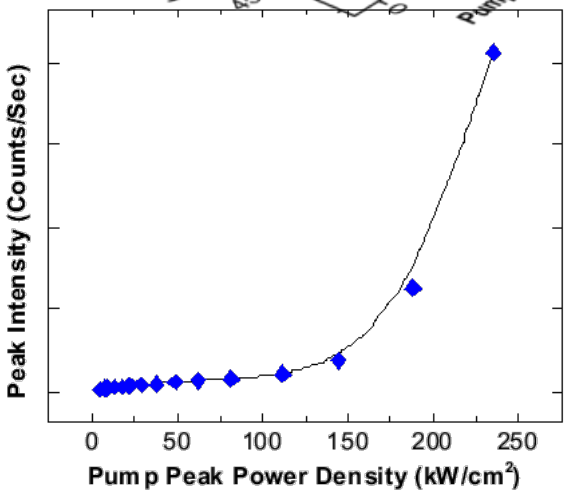
Array Element Dimensions: d=145 nm and a=320 nm.

Pump spot is tunable in size and power density.

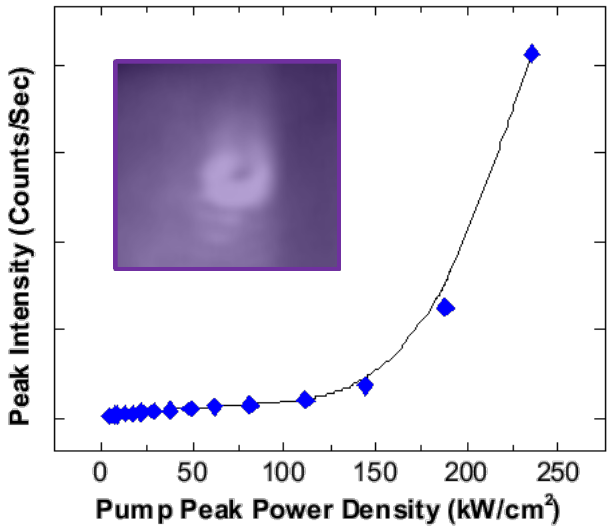


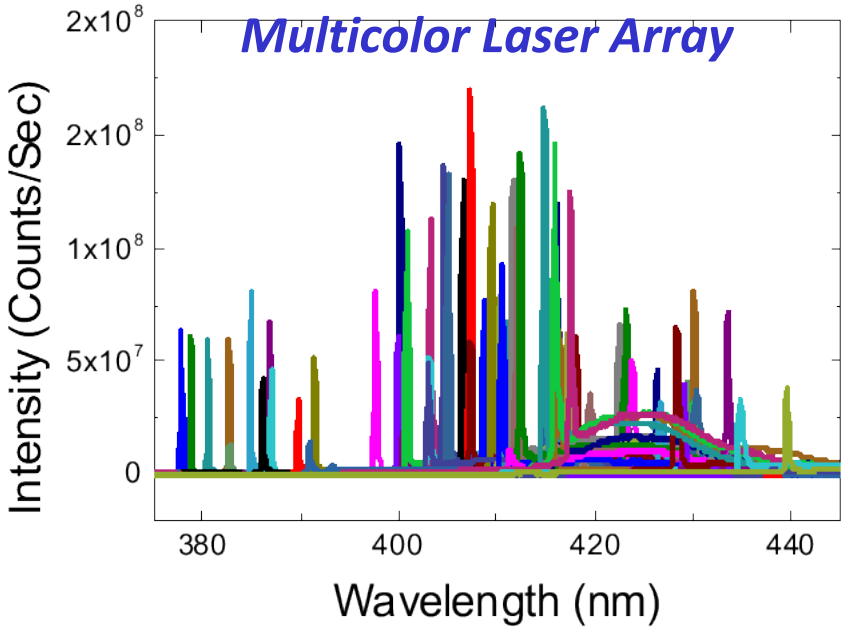


A low lasing threshold is achieved with < 500kW/cm2 for all PC lasers fabricated.



Optical response – low threshold lasing





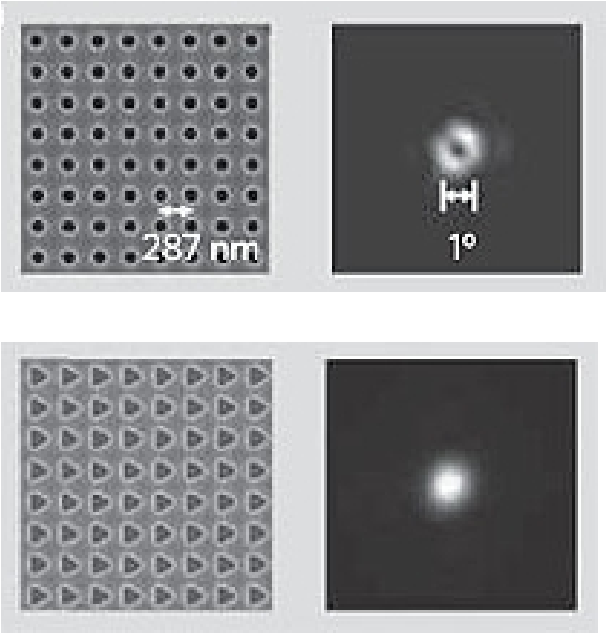
- *A low lasing threshold is achieved with < 500kW/cm2 for all PC lasers fabricated.*
- *Wavelength tunability (lattice constant and nanowire diameter).*
- *Multiple color laser emission on a single epitaxial wafer covering a spectral range from 380-440nm.*
  - *Multiple gain regions can simultaneously lase*
  - *Pathway for enhancing the available lasing spectral range*

Wright, J. B. *et al.* Multi-Colour Nanowire Photonic Crystal Laser Pixels. *Sci. Rep.* **3**, 2982,(2013)

Modifying Extraction and Emission Mode Profile

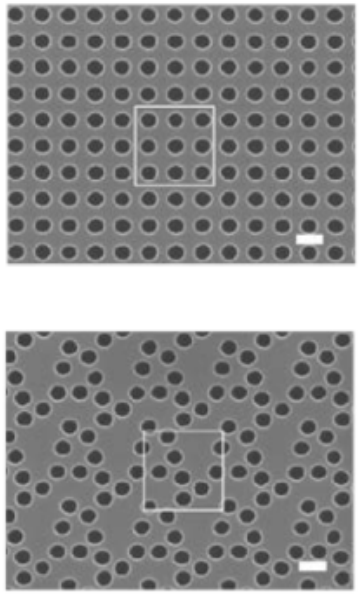
Modify extraction → break mirror symmetries

Method 1



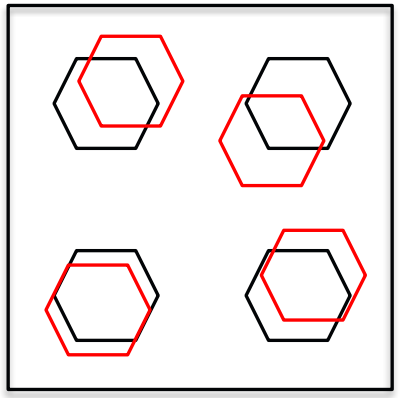
Miyai, E., et al., *Nature*, 441, 946 (2006)
Noda Group

Method 2

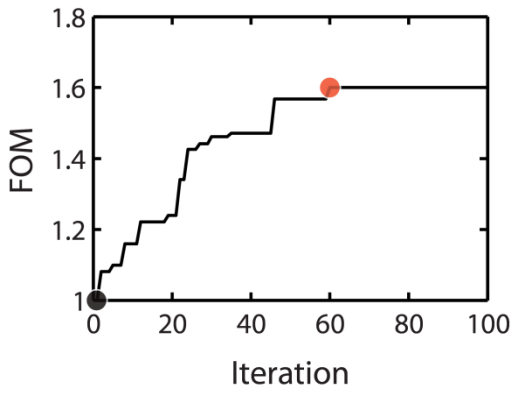


C. Lin, et al., *Optics Express*, 21, A872 (2013)
Povinelli Group

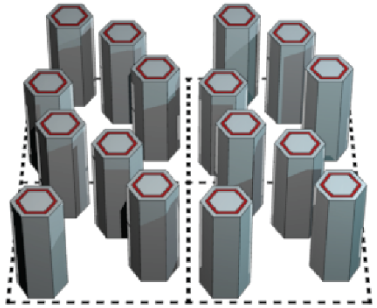
Extraction optimization using Quasi-periodic array

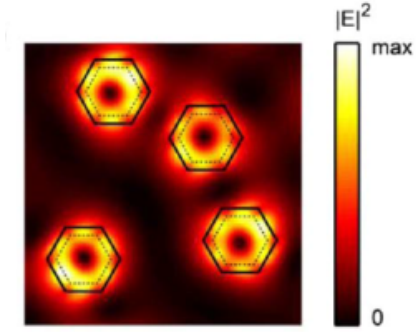


$$\text{F.O.M.} = \frac{\int_{\omega_0-\Delta}^{\omega_0+\Delta} \left|\vec{E}\right|_{Ap}^2 d\omega}{\int_{\omega_0-\Delta}^{\omega_0+\Delta} \left|\vec{E}\right|_{P}^2 d\omega}$$



Optimized geometry:



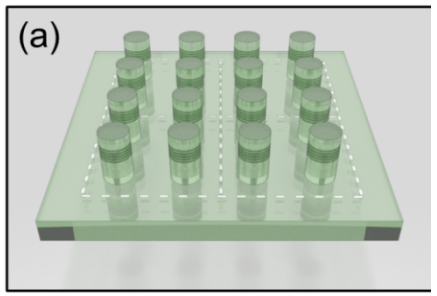


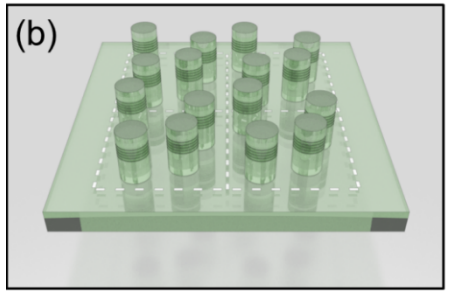
Breaks mirror symmetry

Anderson et al., *Opt. Lett.* 40:2672 (2015)

Light extraction control with PC: Quasiaperiodicity

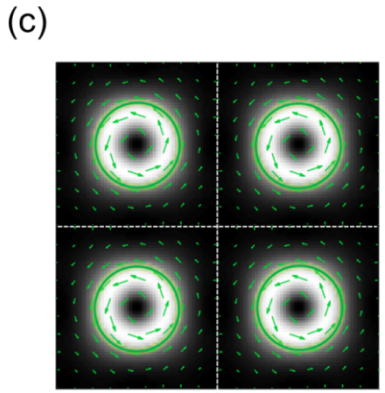
Typical periodic PC

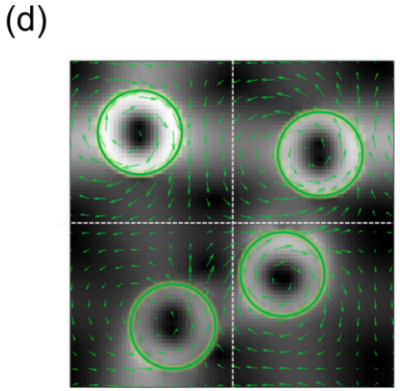




Introduce structural aperiodicity

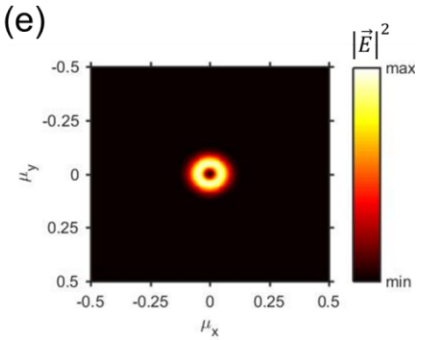
Symmetric field distribution- doesn't couple to far filed

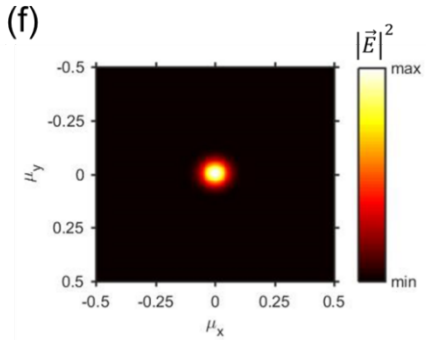




Quasi-aperiodicity induced asymmetric field distribution

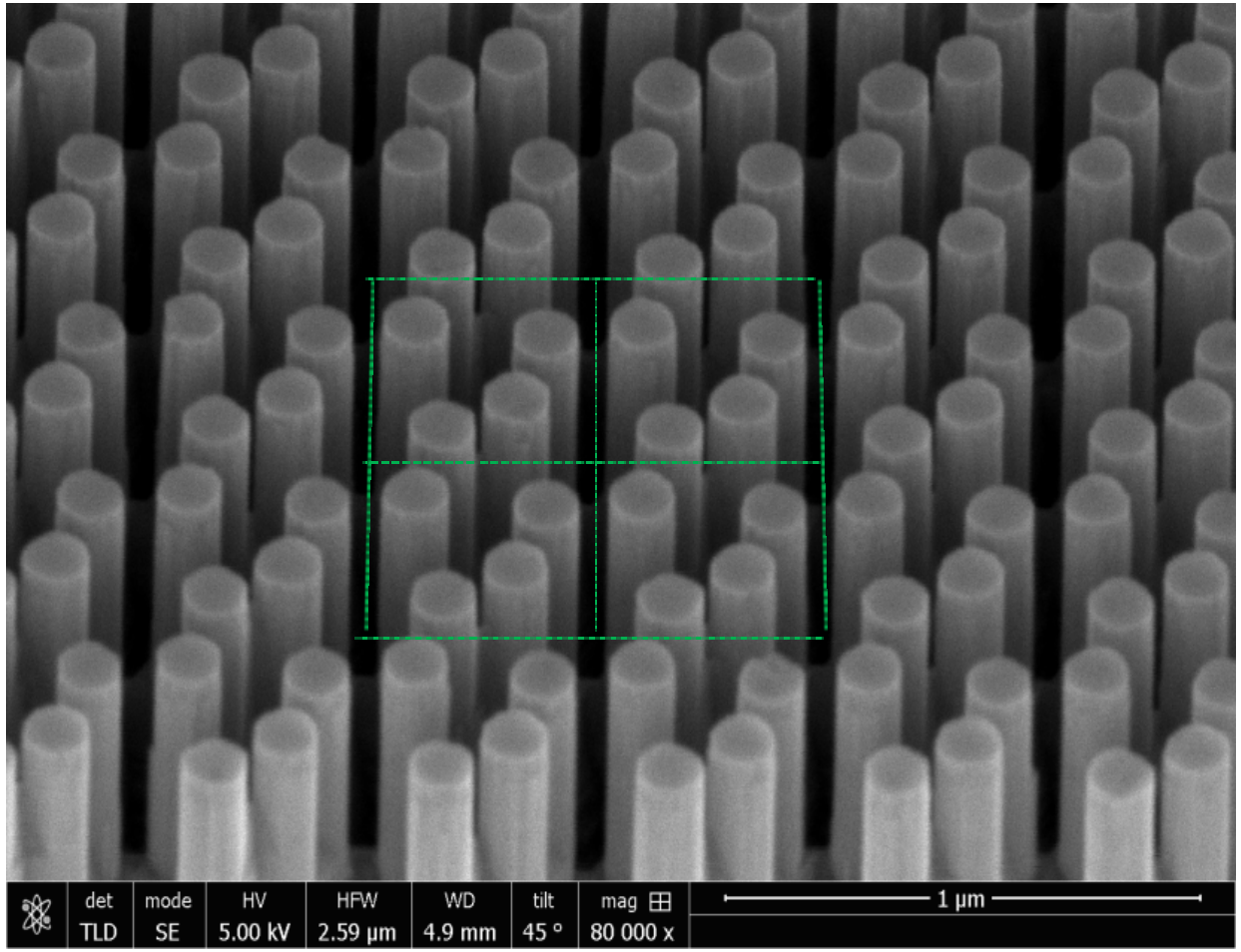
Far field distribution has a null in the normal – "donut beam"





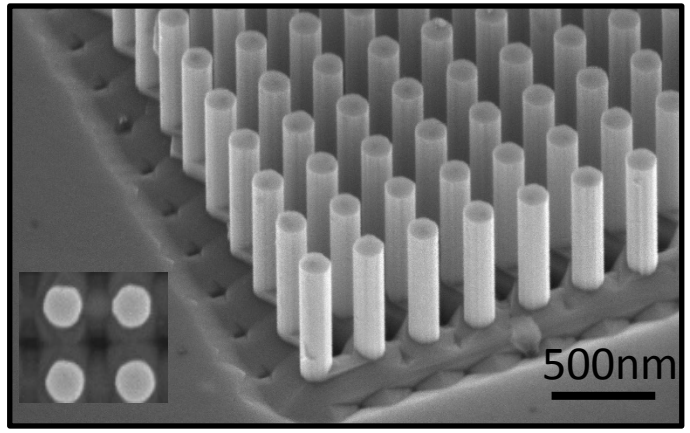
Better far field coupling exhibiting a "Gaussian-like" uniform beam

Quasiaperiodic GaN PhC structures

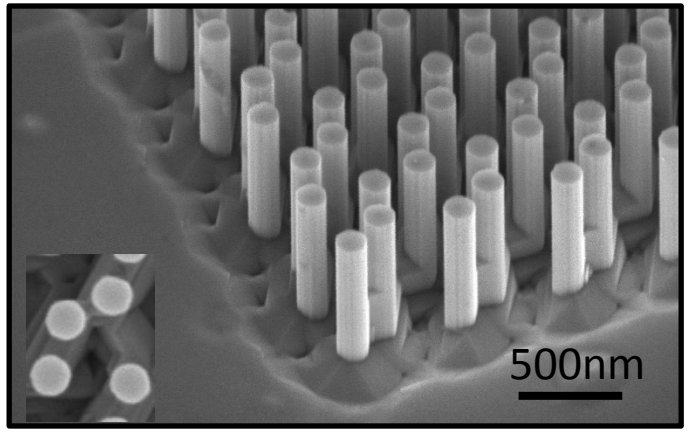


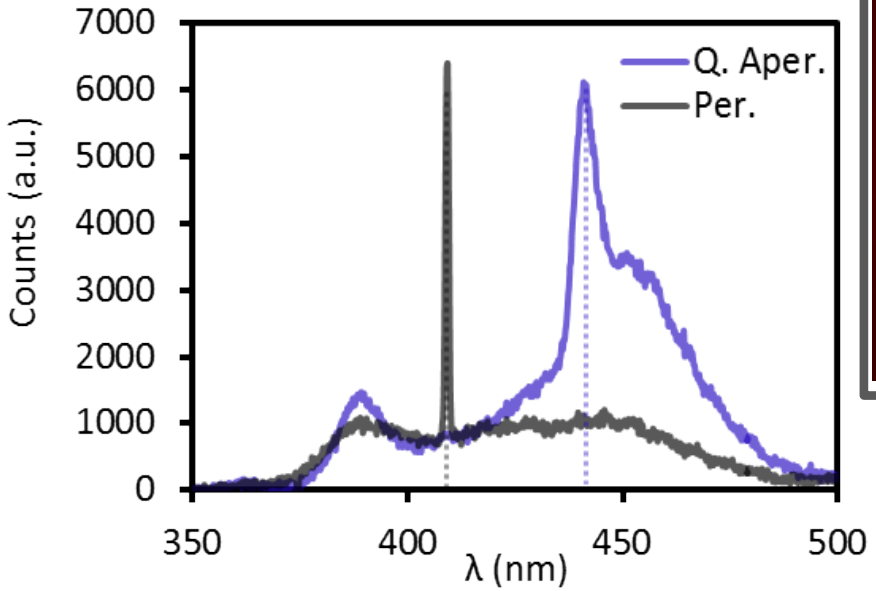
Photoluminescence response

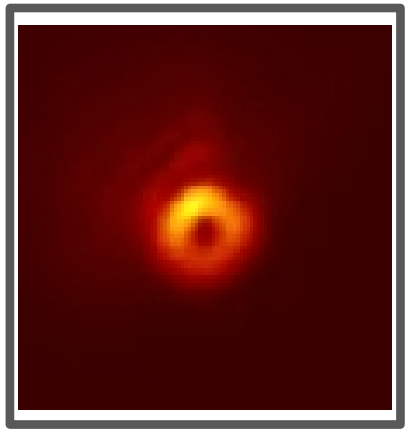
Periodic

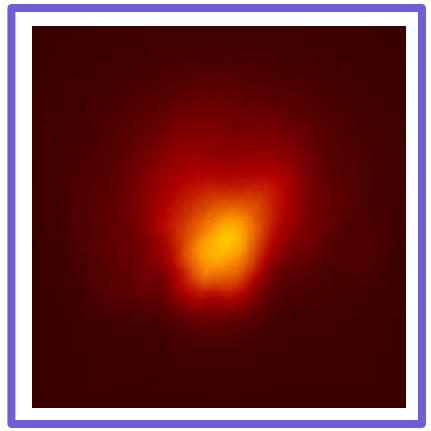


Quasi Periodic







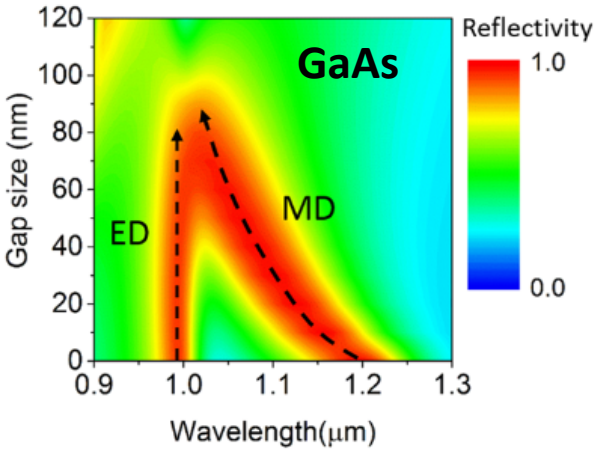


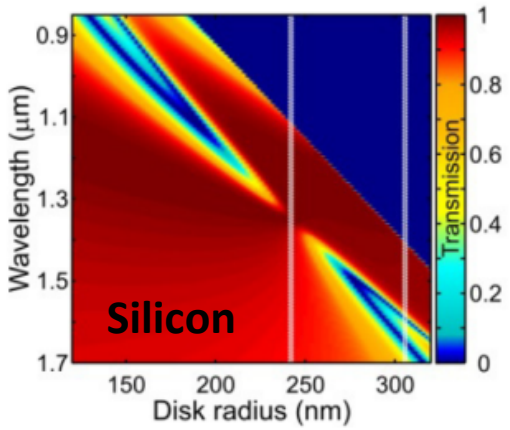
P. D. Anderson, D. D. Koleske, M. L. Povinelli, and G. Subramania, Opt. Mat. Exp7 (10), 3634 (2017)

III-Nitrides for Metasurfaces

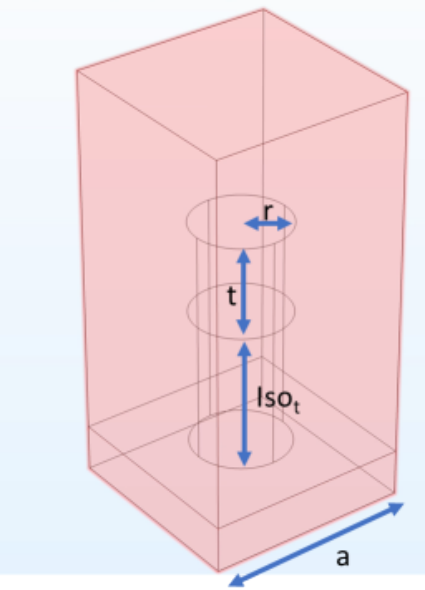
Huygen's Metasurface Design

Full Transmission



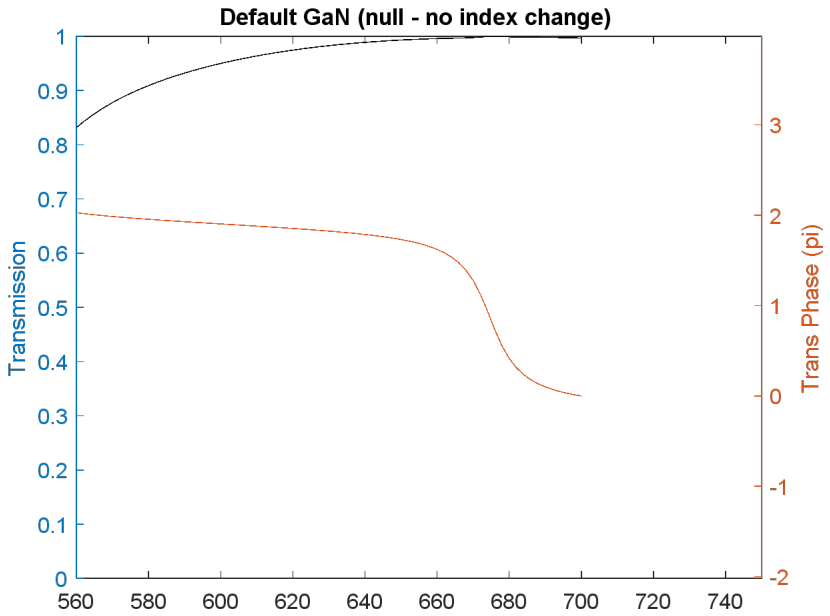


Si Resonator Index = 3.5
Ambient Index = 1.6



t = 161 nm
Iso$_t$ = 300 nm
r = 170 nm
a = 400 nm

GaN Resonator Index = 2.4
Ambient Index = ?

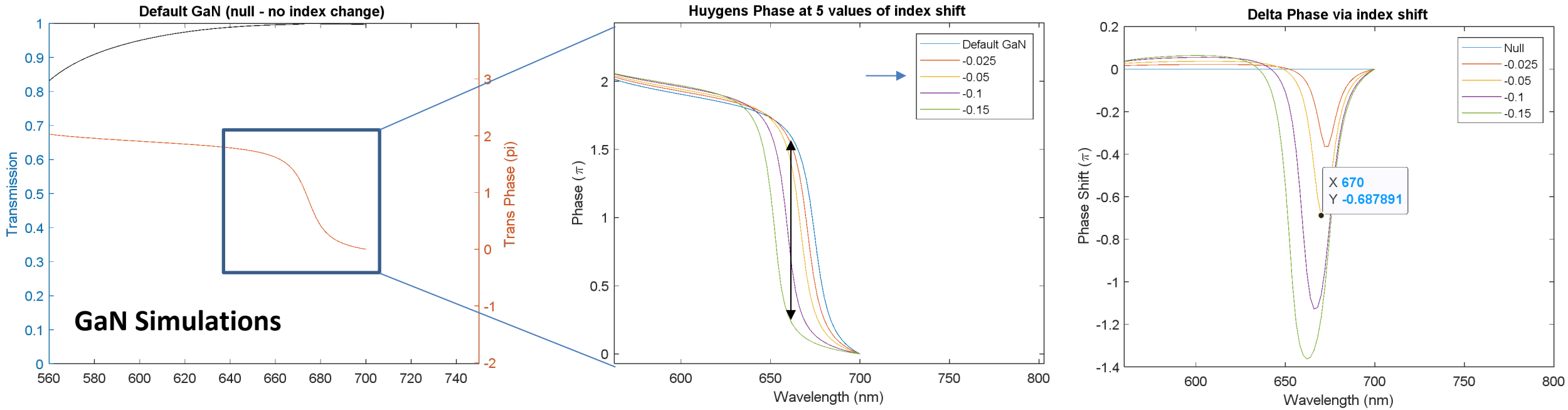


Target design for isolation layer index = 1.4 by using porous GaN

Figures adapted from: Decker, M. Adv. Opt. Mat. 3,6 (2015), Liu, S. Nano Lett. 16.9: 5426, (2016), Liu, S. Nano Lett. 2017, 17, 4297−4303

Tunable Huygen's Metasurface Design

Tuning the phase response

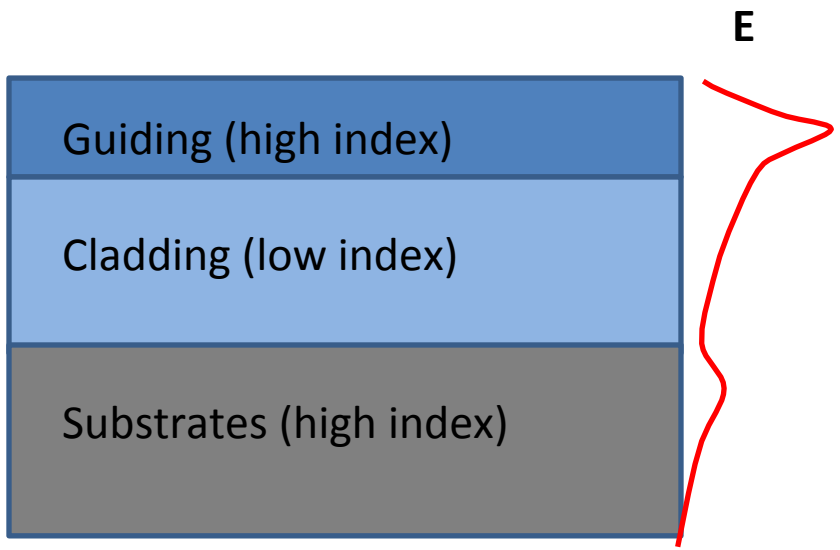


Tuning the resonator index by -0.05 gives

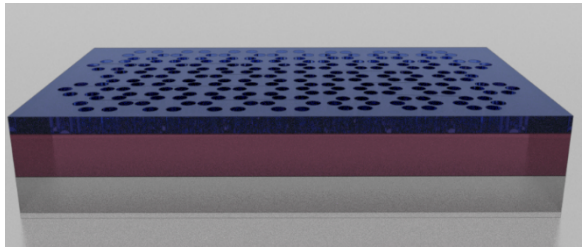
$> \frac{2}{3}\pi$ phase shift at 670 nm

Photonic Devices and Substrate Isolation

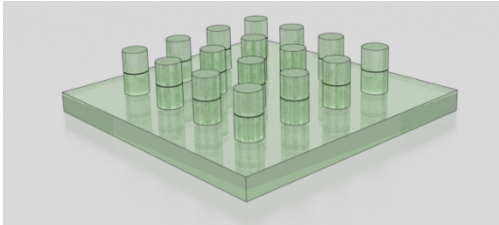
- Nanophotonic devices need isolation from a high index substrates/template
  - Electromagnetic field confined to the active or light guiding layer
  - Low index cladding layer (n ~ 1 – 1.6)
  - Important for photonic crystal or metasurface based devices
  - Optimal advantage of photonic band structure or scatterer resonance

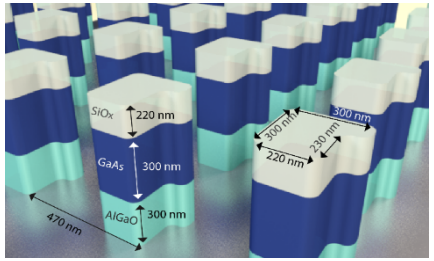


Hole array PhC



Nanowire PhC

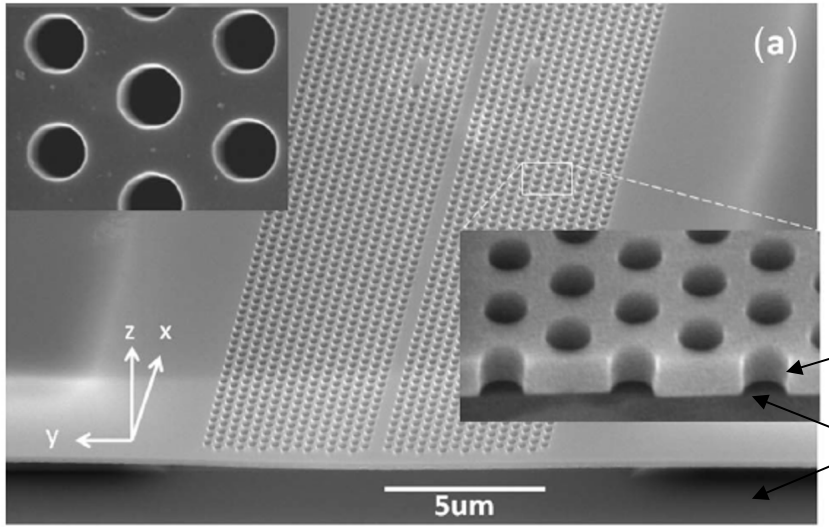




Metasurface

Hole-Array Photonic Crystals

SOI based PhC

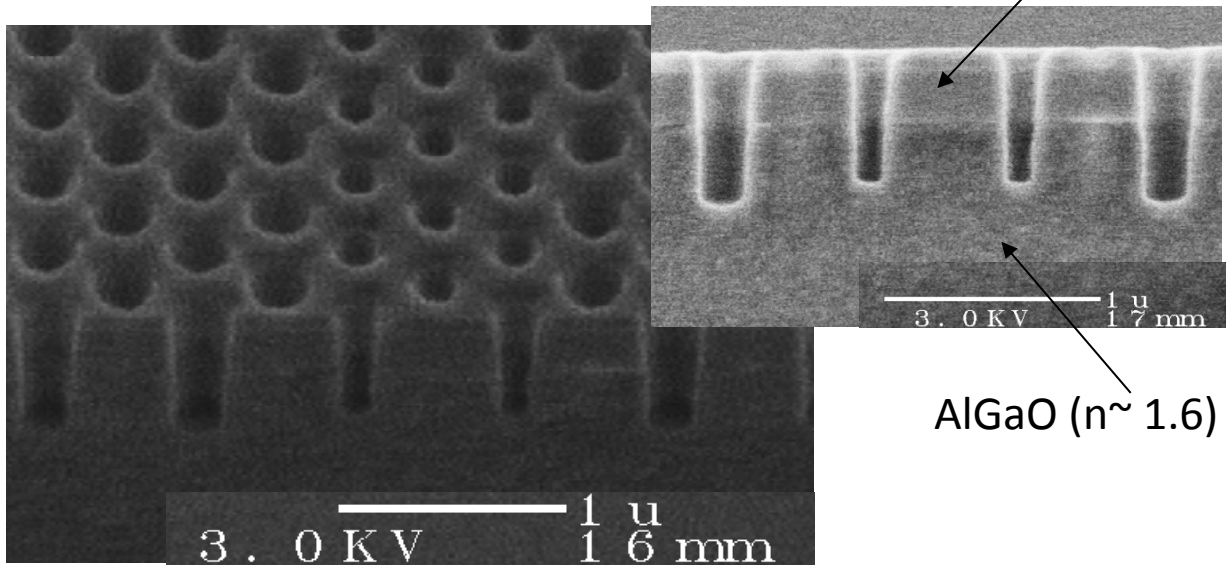


Si (n~ 3.4)

Air

T.S.Luk et. al., JOSA. B **28** (6), 1365 (2011).

GaAs/AlGaAs based PhC



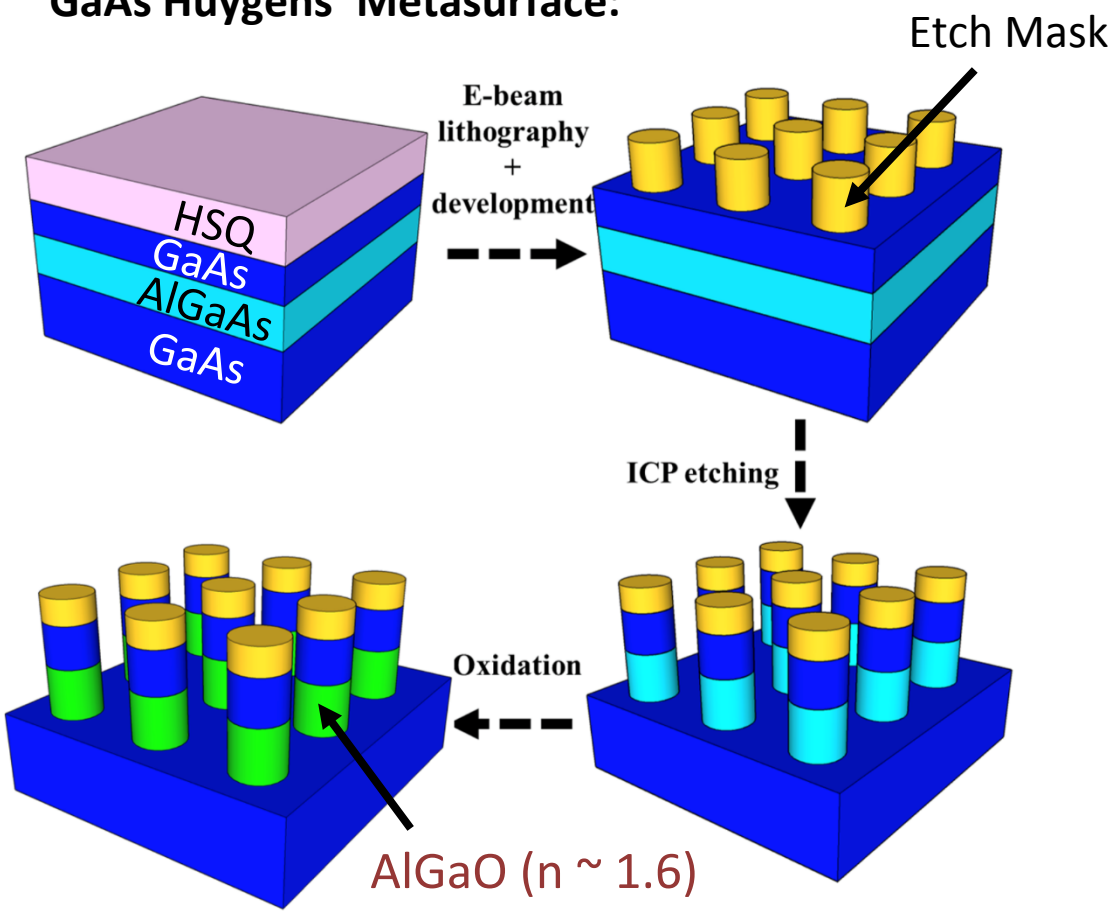
GaAs (n~ 3.4)

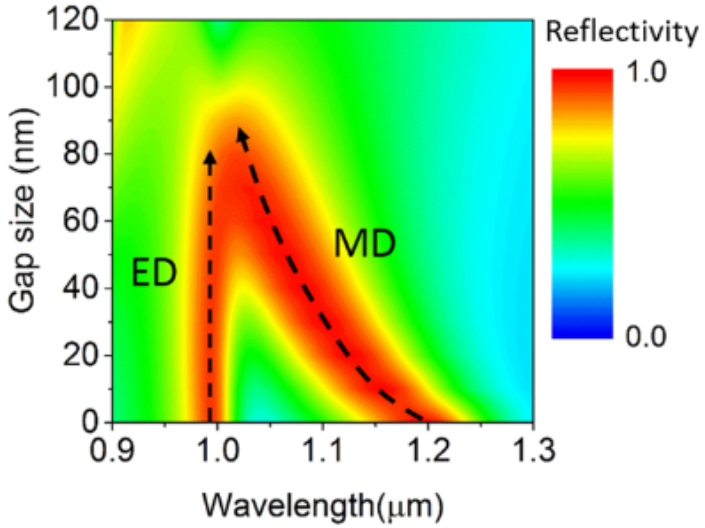
AlGaO (n~ 1.6)

- Si and GaAs have index (n ~ 3.4) can be oxidized to a lower index oxides like SiO2 or AlGaO with lower index (n < 1.7)
  - Cladding or Etched to form membranes
- **III-nitrides do not have natural easily oxidizable low index oxides**
  - **Hole array PhC devices are challenging in III-N**

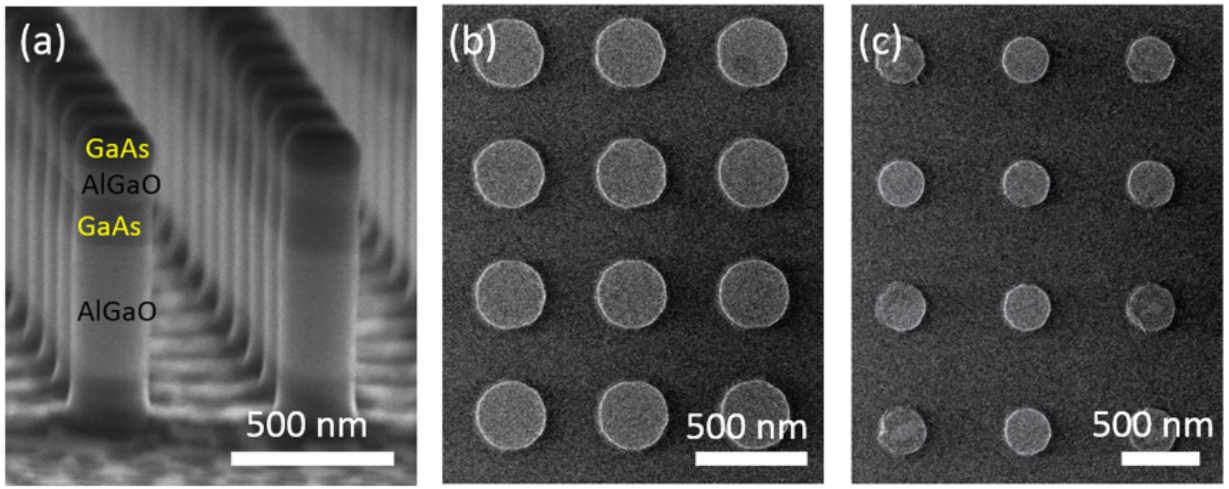
Low index layer in III-V for Optical Isolation

GaAs Huygens' Metasurface:





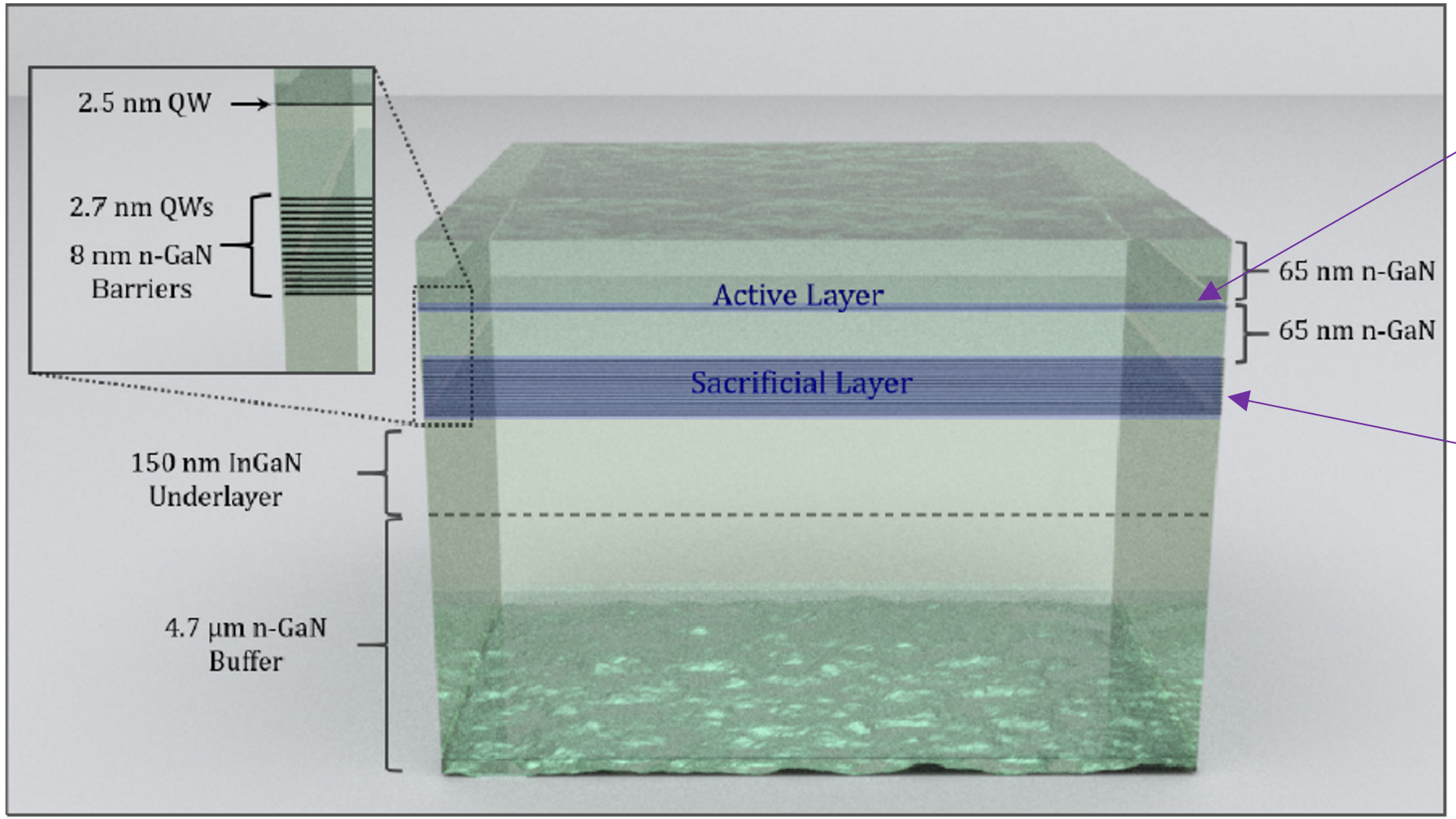
Design for overlap of ED and MD (Huygens' condition)



III-nitrides do not have natural easily oxidizable low index oxides – Substrate Isolation challenging in III-N

Figures adapted from: Liu, S. Nano Lett. 16.9: 5426, (2016)
Liu, S. Nano Lett. 2017, 17, 4297−4303

III-Nitride Membrane PhC : One approach



InGaN SQW low Indium (**10%**)

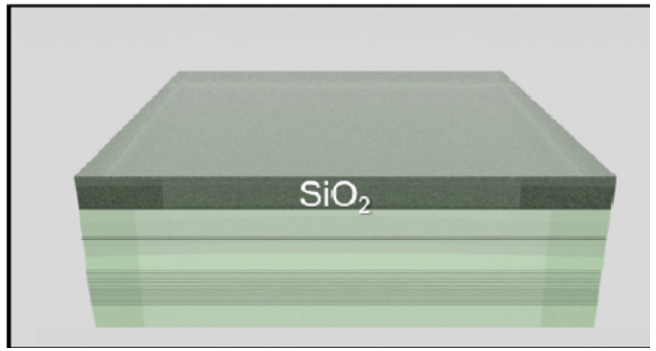
InGaN MQW higher Indium (**16%**) sacrificial layer

Epi Structure with a bottom sacrificial MQW layer

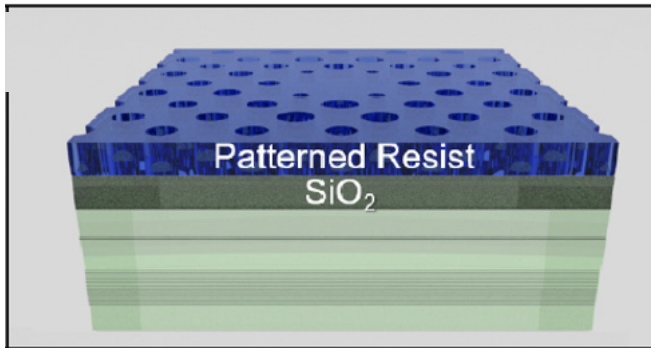
Figures reprinted/adapted from Anderson, P. D.; Fischer, A. J.; Koleske, D. D.; Gunning, B. P.; Subramania, G., *Optical Materials Express* **2018, *8*** pp3543-3550.; Copyright 2018 OSA.

Fabrication steps

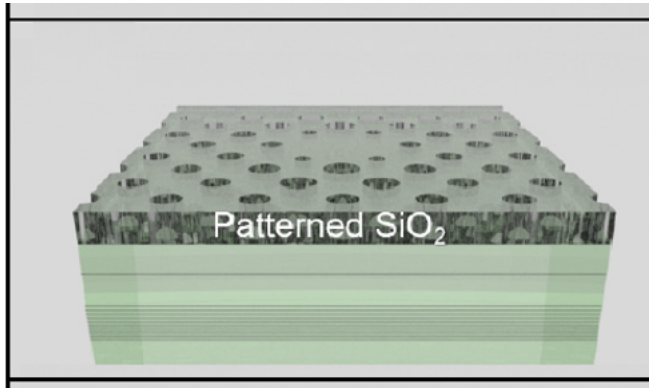
Deposit SiO_2 hardmask



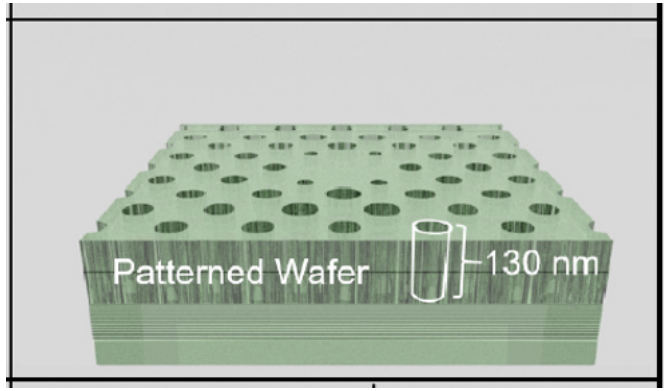
EBL pattern in PMMA



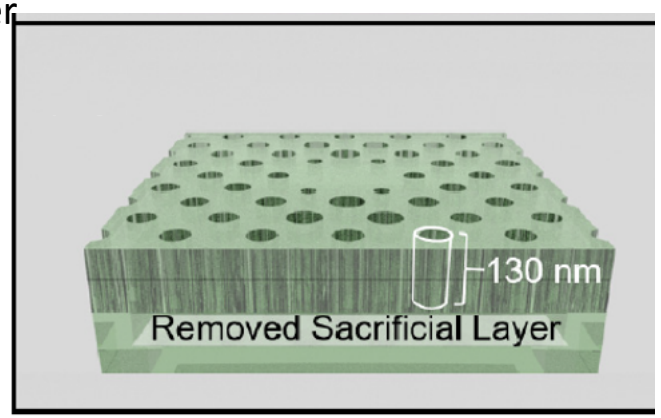
Etch Hardmask



Etch III-nitride active layer through patterned hardmask



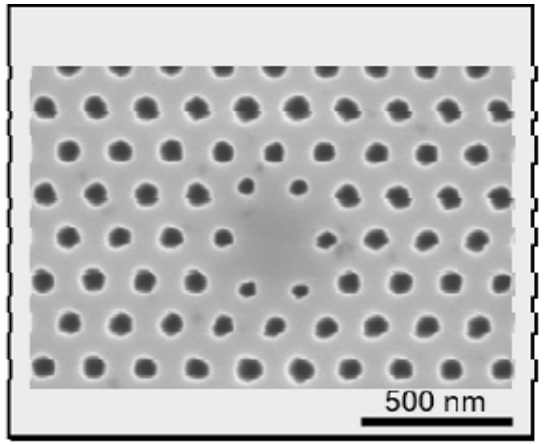
Remove sacrificial multiquantum well layer

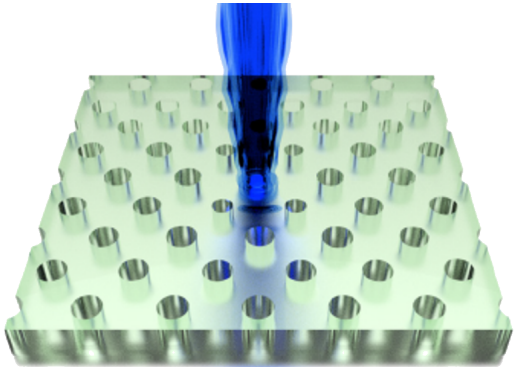


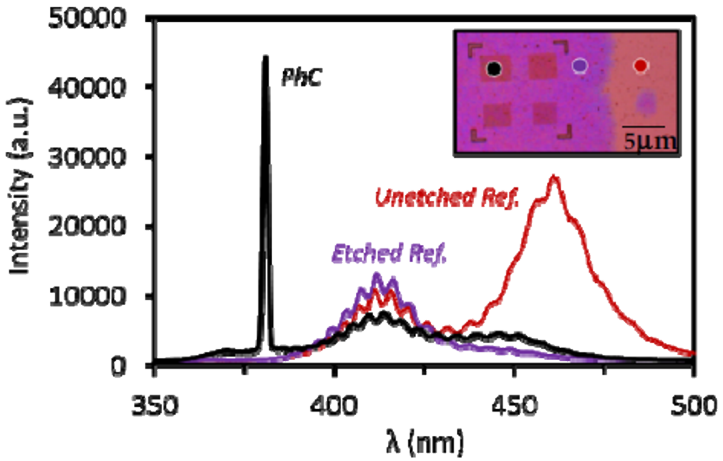
Figures reprinted/adapted from Anderson, P. D.; Fischer, A. J.; Koleske, D. D.; Gunning, B. P.; Subramania, G., *Optical Materials Express* **2018, *8*** pp3543-3550.; Copyright 2018 OSA.

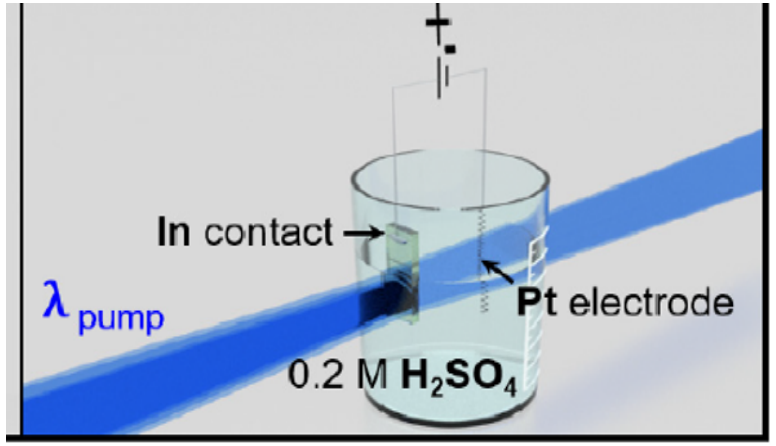
Photoelectrochemical Etching (PEC)

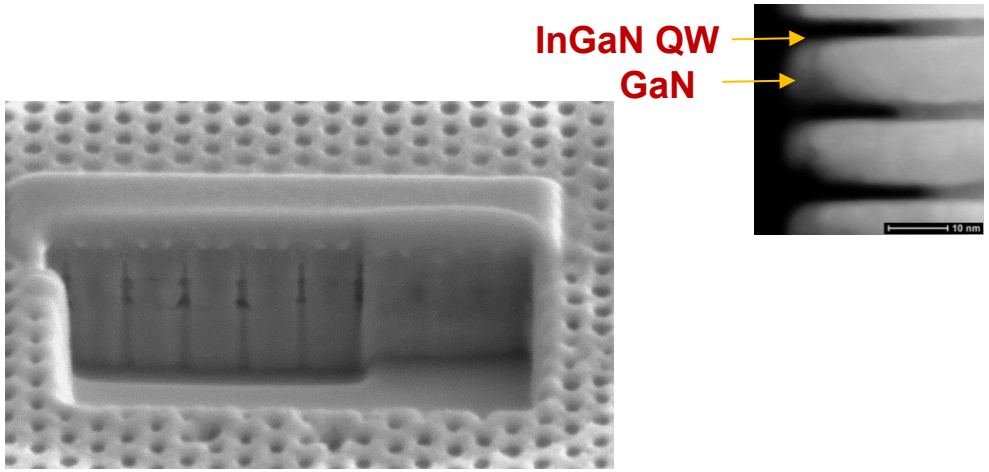
- Electrochemical etch is performed under laser illumination
- Laser wavelength is selected such that it is shorter than the energy gap of 16% InGaN but longer than that of 10% InGaN
- Selective etching of 16% InGaN MQW
- Creates low index cladding layer











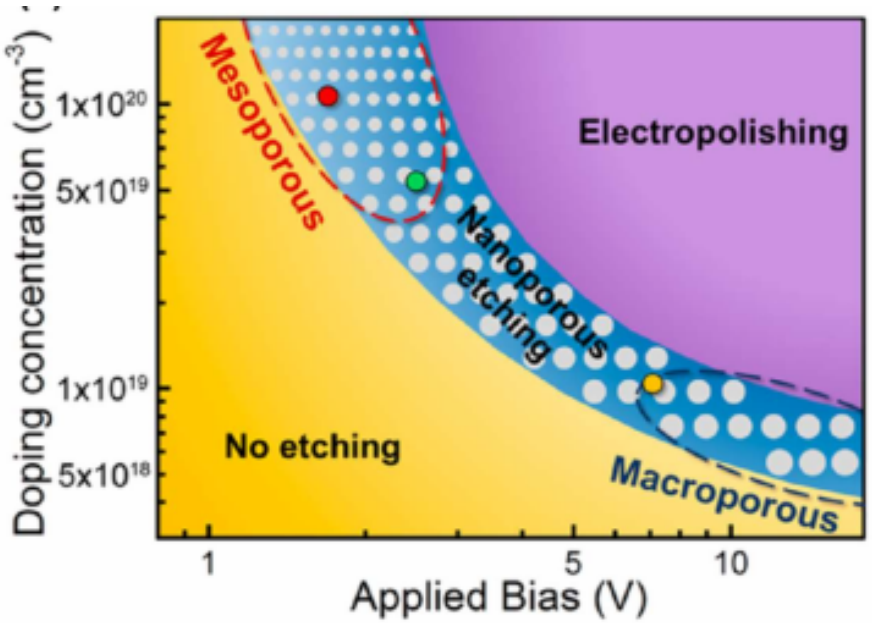
- Removal of InGaN QWs by PEC reduces cladding layer index but procedure is challenging
- Hard to scale for thicker cladding

Anderson, P. D.; Fischer, A. J.; Koleske, D. D.; Gunning, B. P.; Subramania, G., *Optical Materials Express* **2018,** *8* (11), 3543-3550.

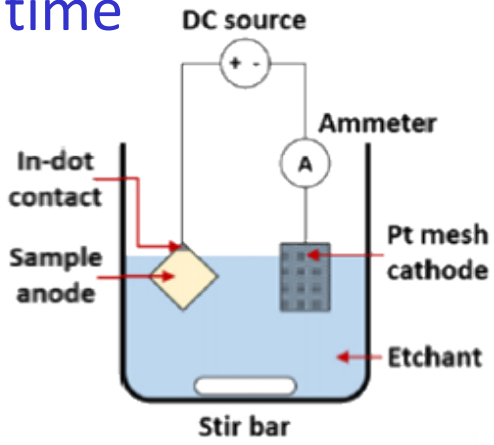
Nanoporous III-N Low Index Layer

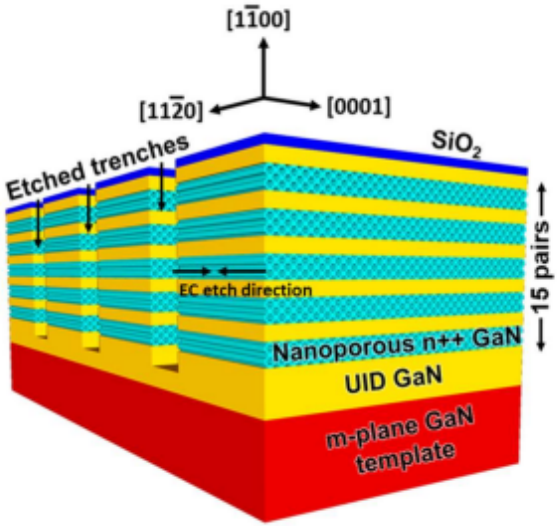
Electrochemical (EC) etching of doped III-N layer in chemical bath

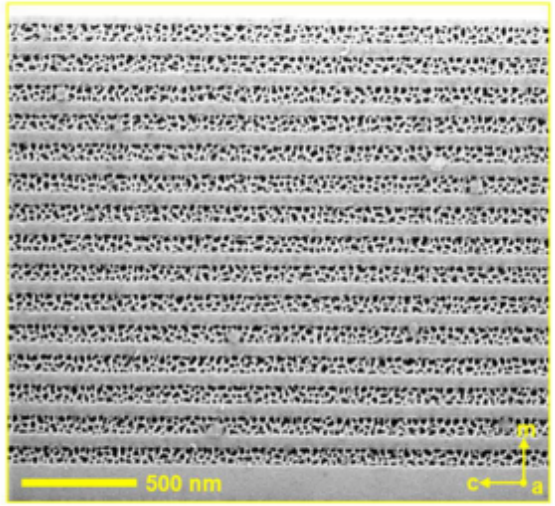
- Etching conditions - applied voltage, doping concentration, etching time



Feezell Group (UNM)





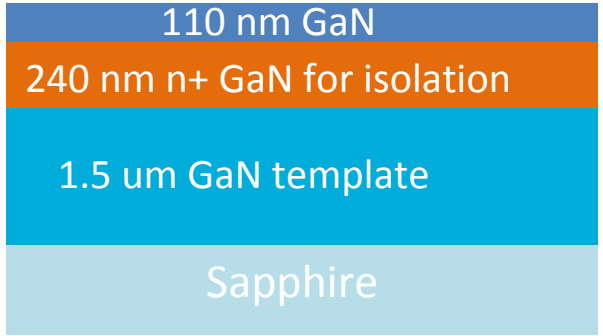


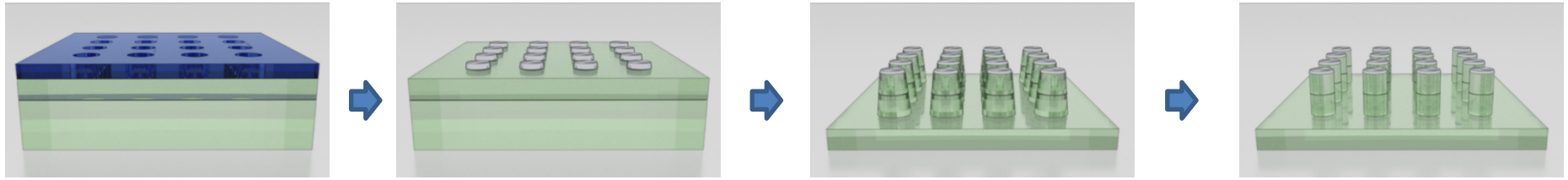
Approach is flexible and scalable

- **Enables control of porosity a through control of etch conditions**

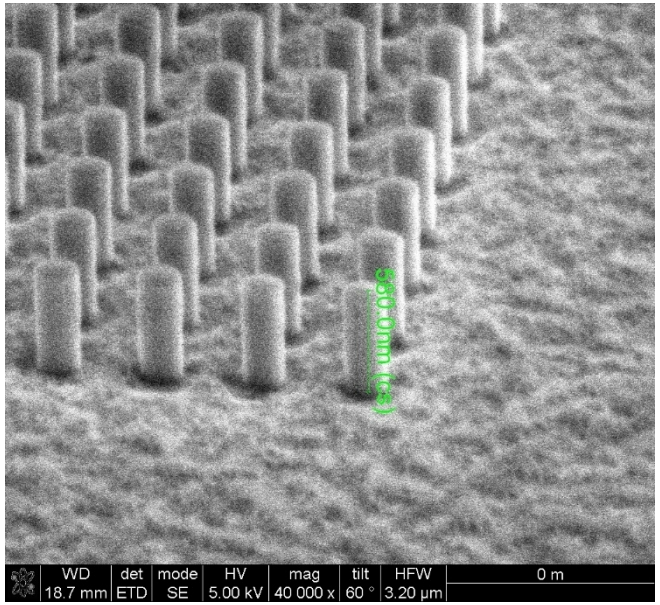
Figures adapted from Mishkat-Ul-Masabih, S et. al. *Applied Physics Letters* **2018,** *112* (4), 041109

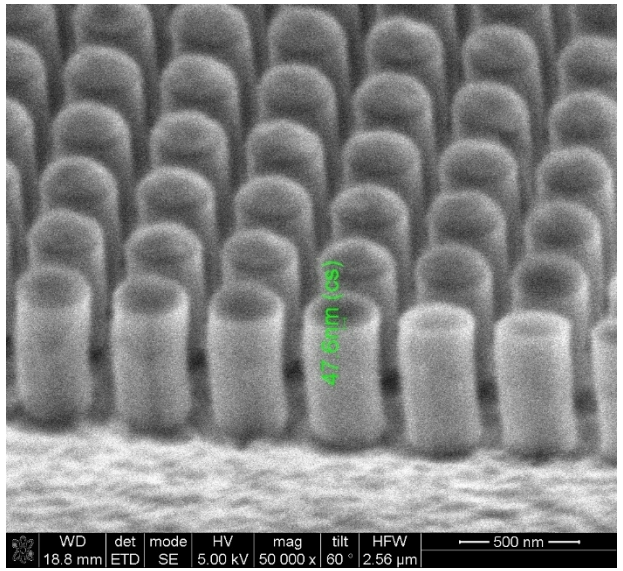
III-N Nanowire Array Resonators





EBL pattern in PMMA → Ni evaporation and lift-off → Cl_2 based dry etch → KOH based wet etch



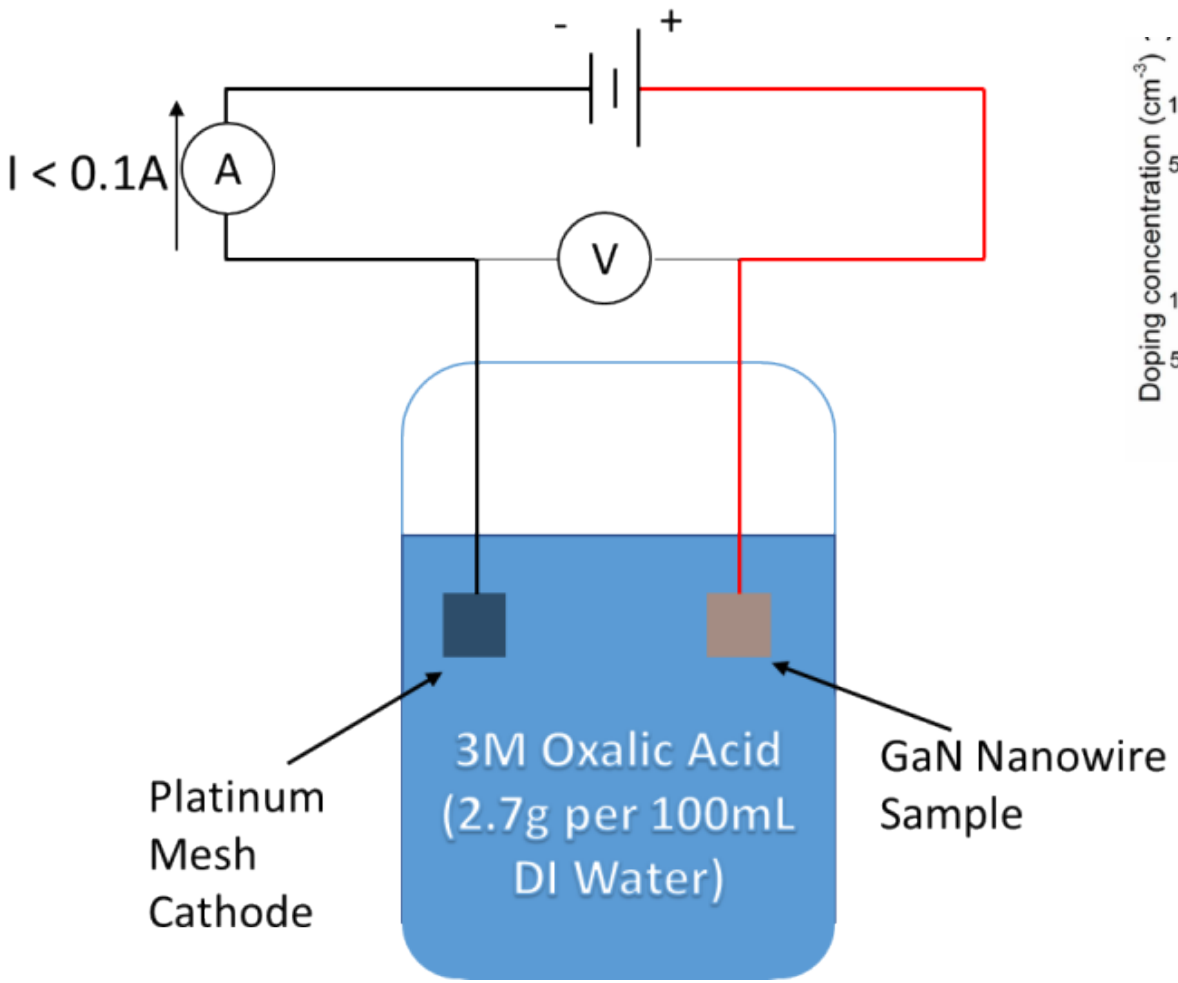


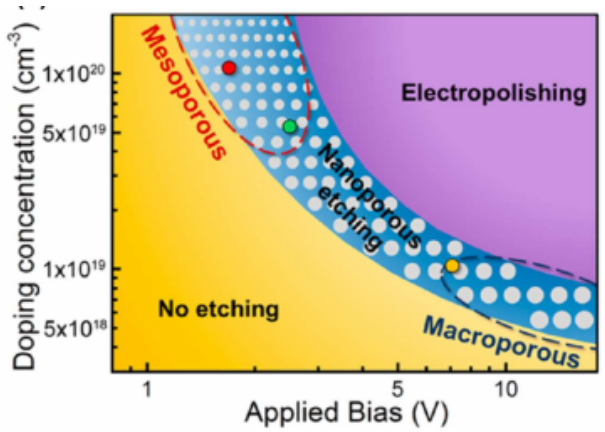
Demonstration of cylindrical GaN nanowire array with smooth side walls

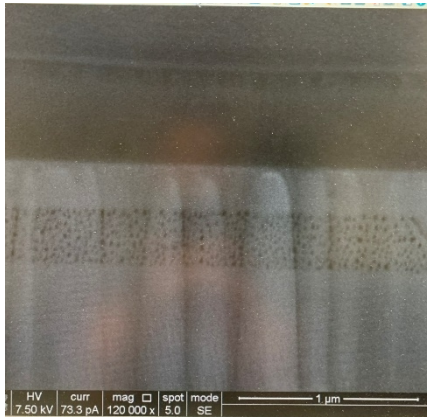
Electrochemical Etching Process

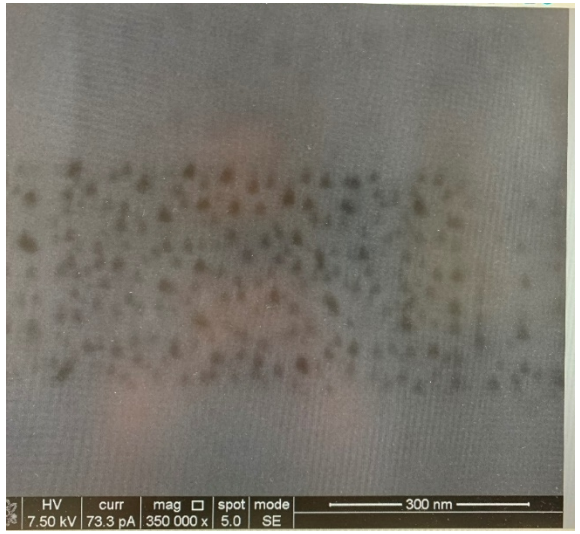
Electrochemical etching of doped GaN layer in acidic solution (Z. Meinelt / D. Feezell (UNM))

- Results in nanoporous region with lower effective refractive index





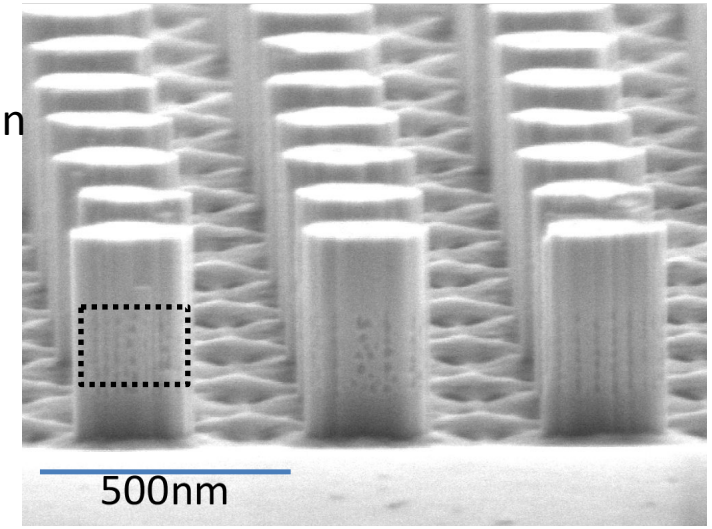


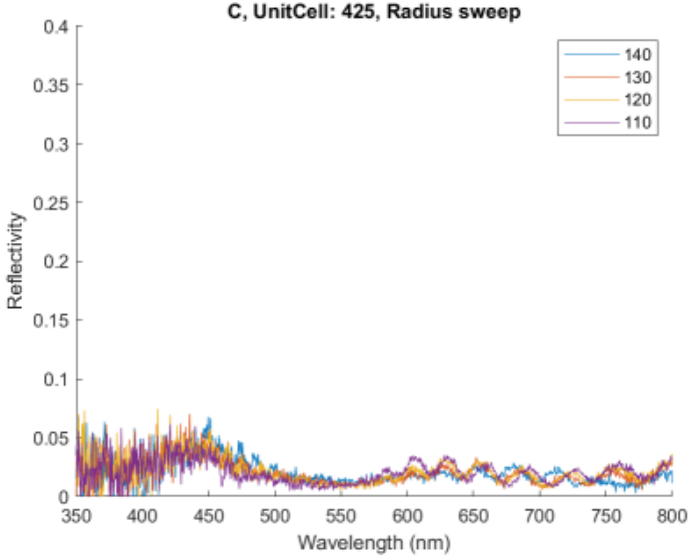


Electrochemical Etch of Nanowire Resonators

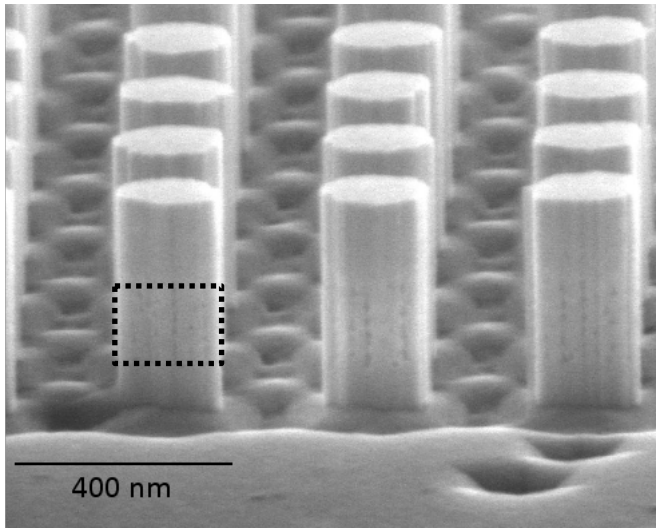
Etch time : 12min

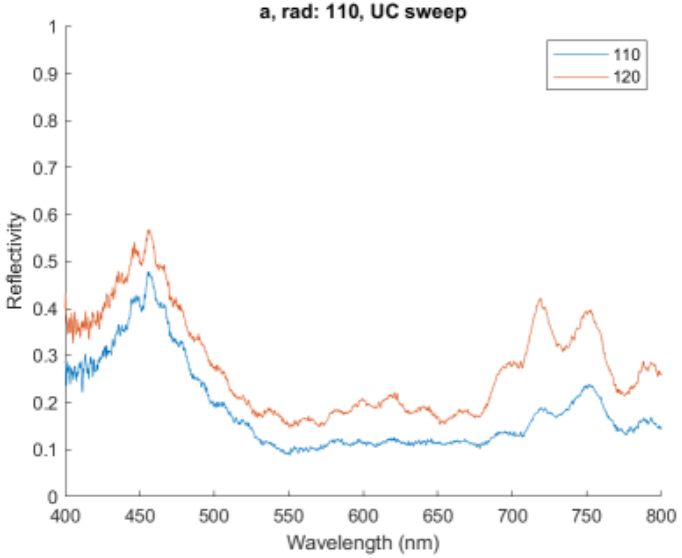
Etch voltage: 6V

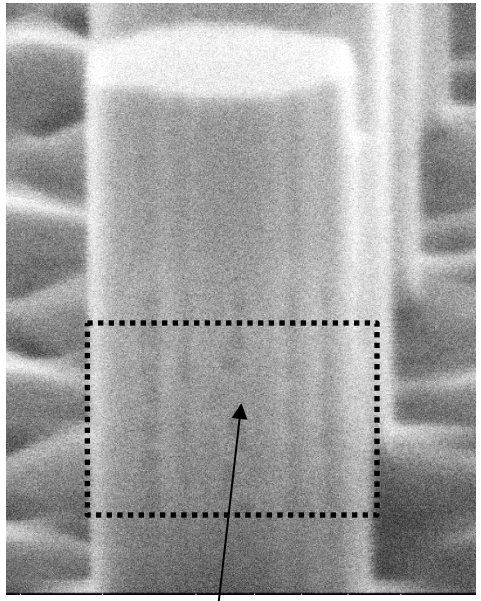




Etch voltage: 7V







Nanoporous GaN region
(n~ 1.2e-19 cm^{-3})

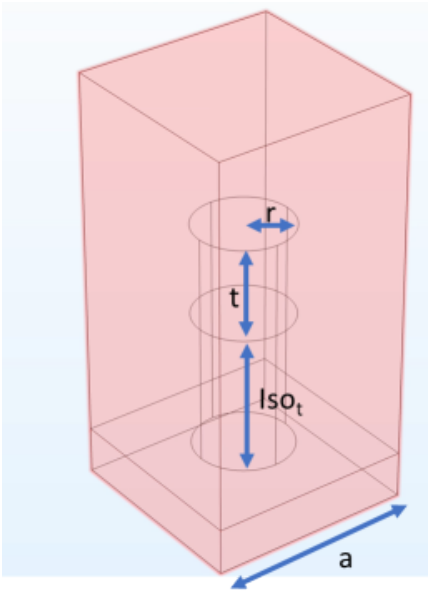
EC etching shows reduction in refractive index evidenced in optical response

Porosity Characterization

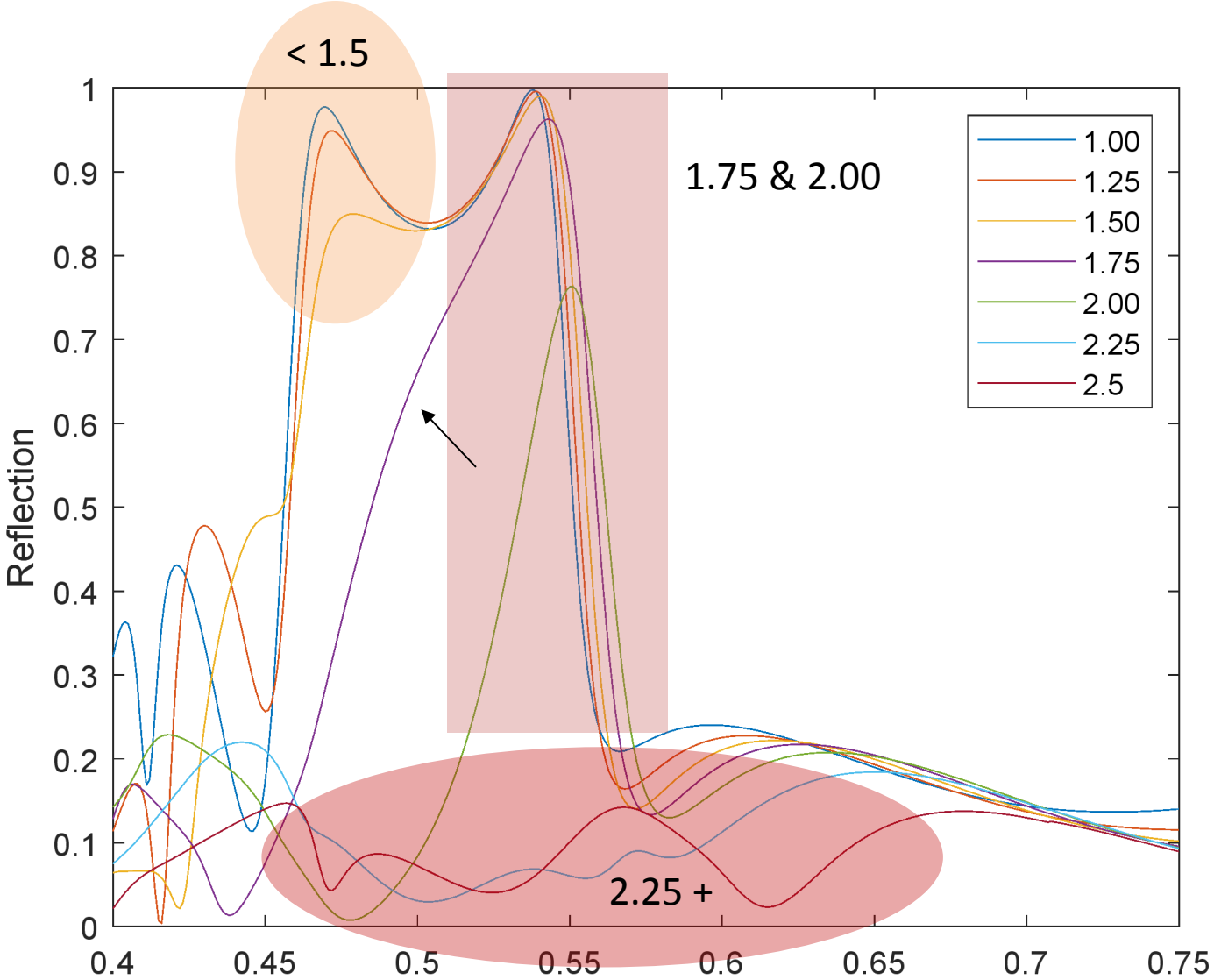
Targeting an effective index of < 1.5

Huygens' MS has complicated optical response when isolation layer index is incorrect

MS with separated ED and MD is used to guide fabrication



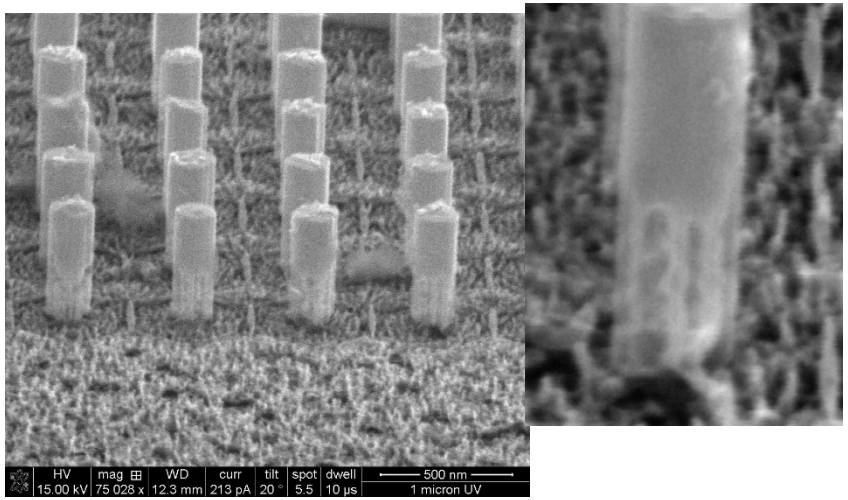
t = 200 nm
Iso_t = 300 nm
r = 105.2
a = 440 nm



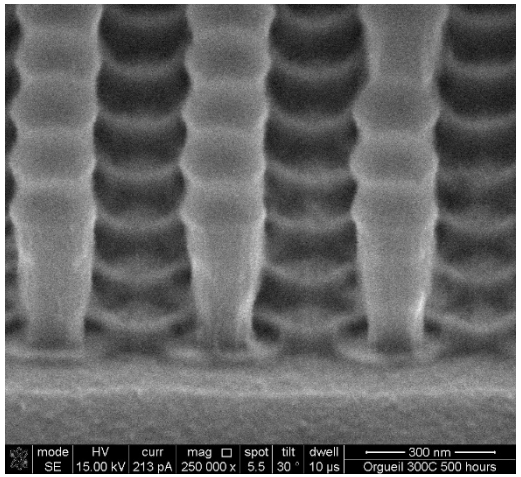
Porosity Characterization

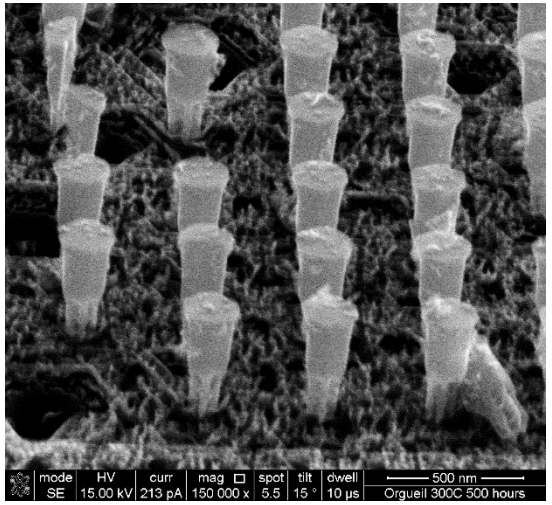
(24 V, 12 min)

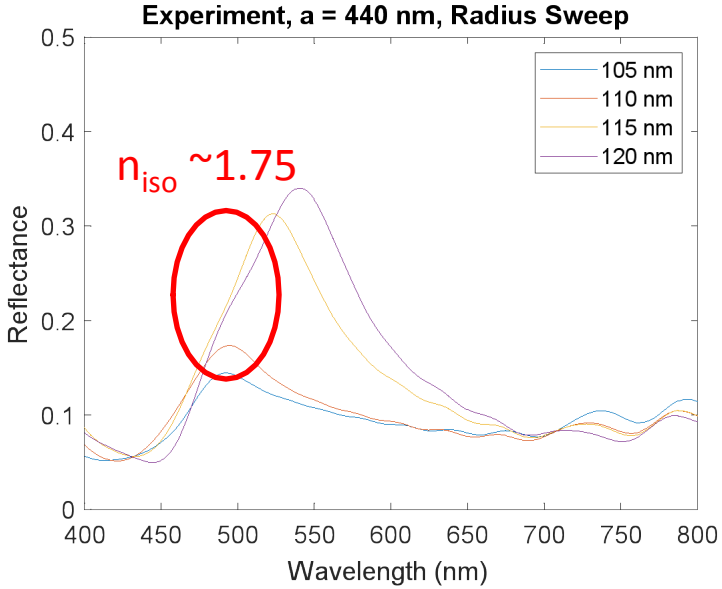
EC etch



Blanket wet etch (KOH) + EC etch

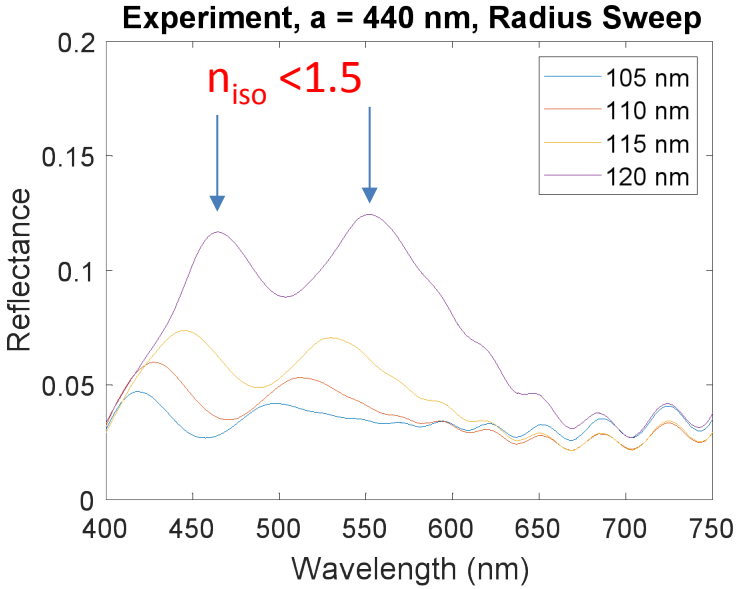






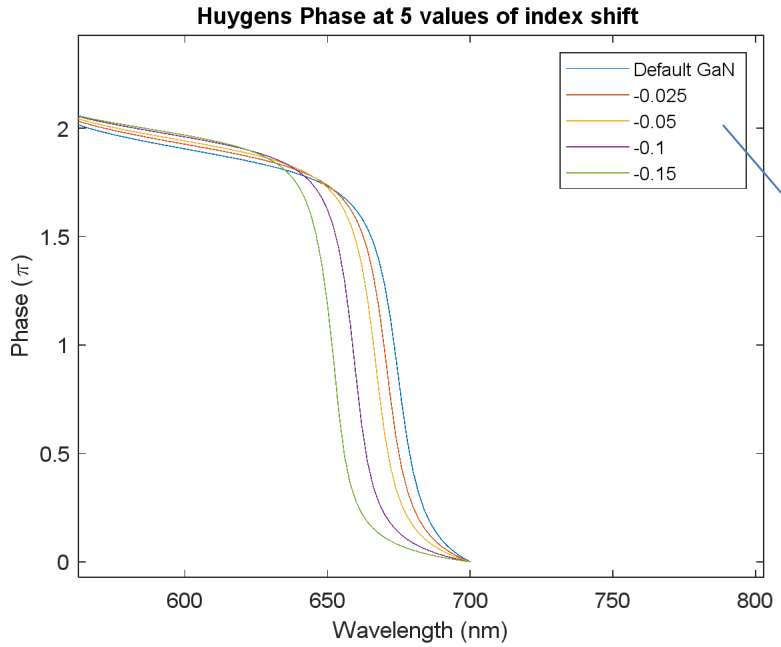
Using our characterization design, the nanowire resonators show a clear reflectivity response enabling porosity/effective index characterization.

With the additional wet etch the porosity target enabling our Huygens' MS has been achieved!

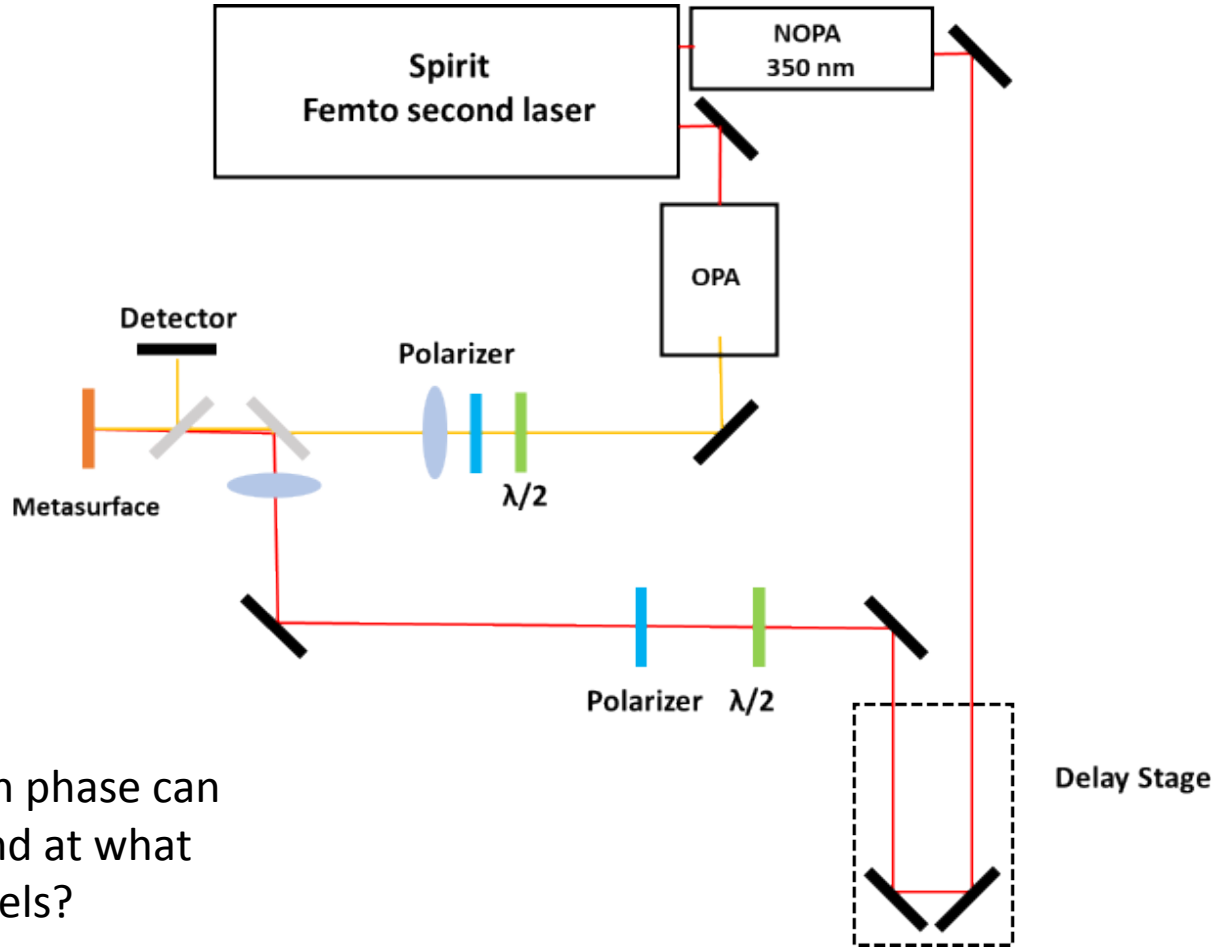


Tuning Characterization

Characterize the transmission and phase response of the Huygens' MS as the resonator index is tuned (via ultrafast optical pumping)



How much phase can we get, and at what power levels?



Summary

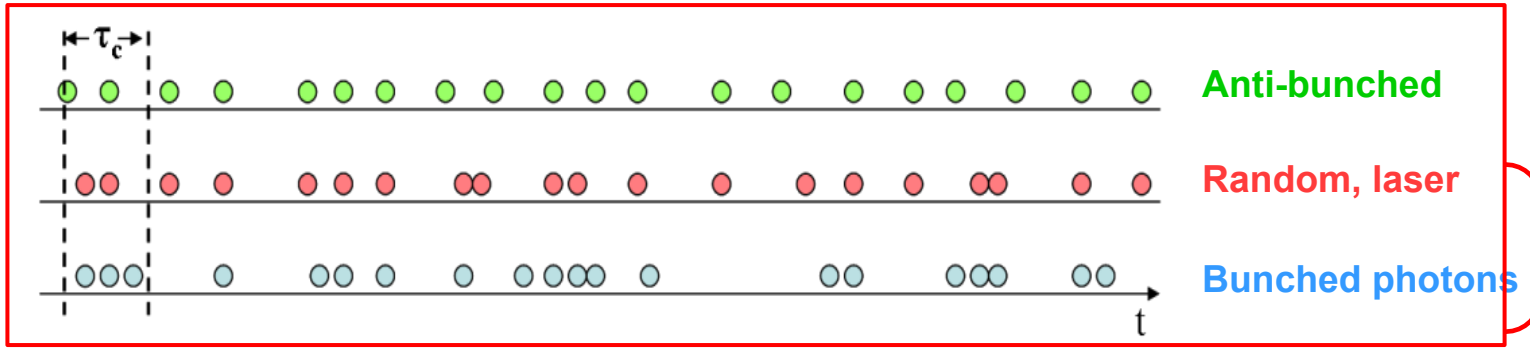
- Role of nanostructuring in light control
- 2D Nanowire Photonic Crystals exhibits vertical lasing emission
  - Can modify emission profile
- III-Nitrides for Metasurfaces can enable tunable response
  - Substrate isolation cladding will be important; EC etch provides an elegant route
- Quantum Dots for Single Photon Sources (time permitting)
  - Photo electrochemical etch can enable size controlled QDs

Thank you for your attention!

Back up slides

Quantum Dots for Single Photon Sources

Single Photon Source: Photon Statistics



Quantum

g(2)(t = 0) <1

e.g., SPS

Classical

g(2)(t = 0) ≥ 1

e.g.,Thermal,LED, Laser

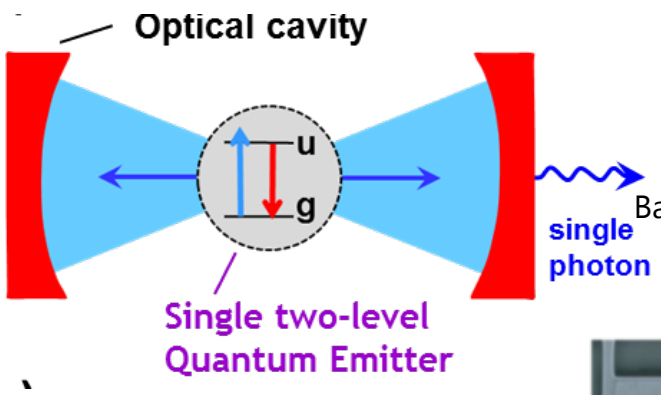
source: J.S. Lundeen

- **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

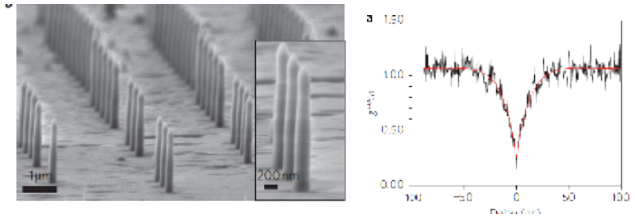
Desired properties of practical single photon sources (SPS)

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

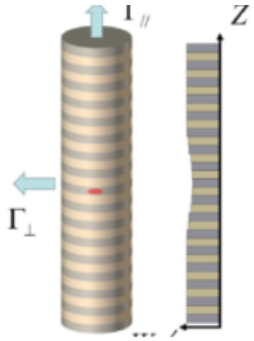
Single Photon Source based on Quantum Dots



Diamond

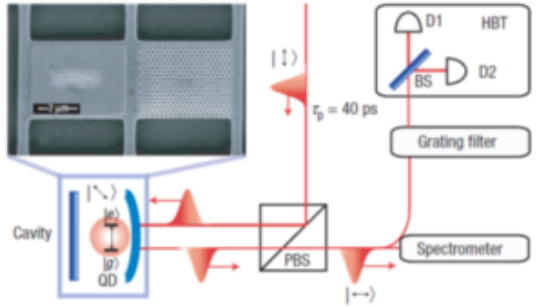


Babinec, T. M. *et al. Nat Nano* **5**, 195-199 (2010).

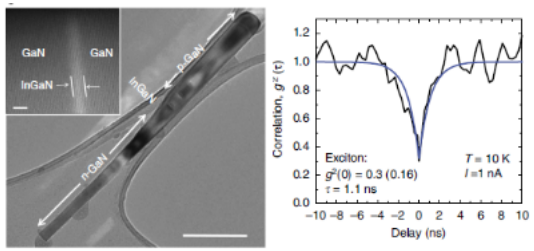


Portalupi, S. L. *et al. Nano Lett.* **15**, 6290-6294, d (2015).

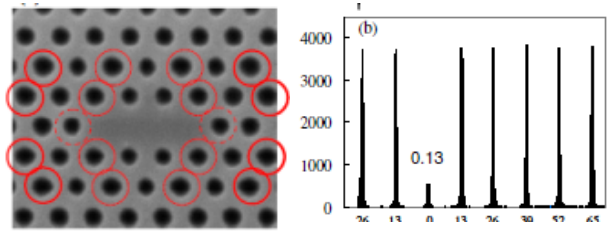
III-V



Faraon, A. *et al.Nat. Phys.* **4**, 859-863, (2008).

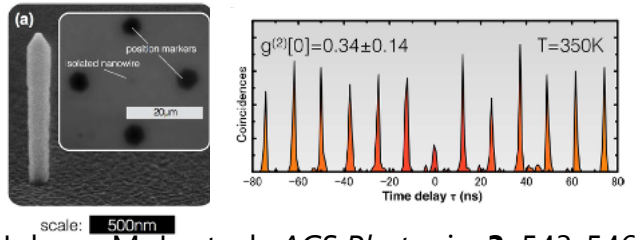


Deshpande, S., Nat.com. **4**, 1675(2013)

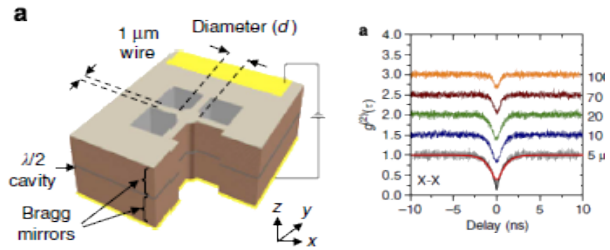


Toishi M., et. al, J. Opt. Exp., **17** , 146185(2009)

III-N



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



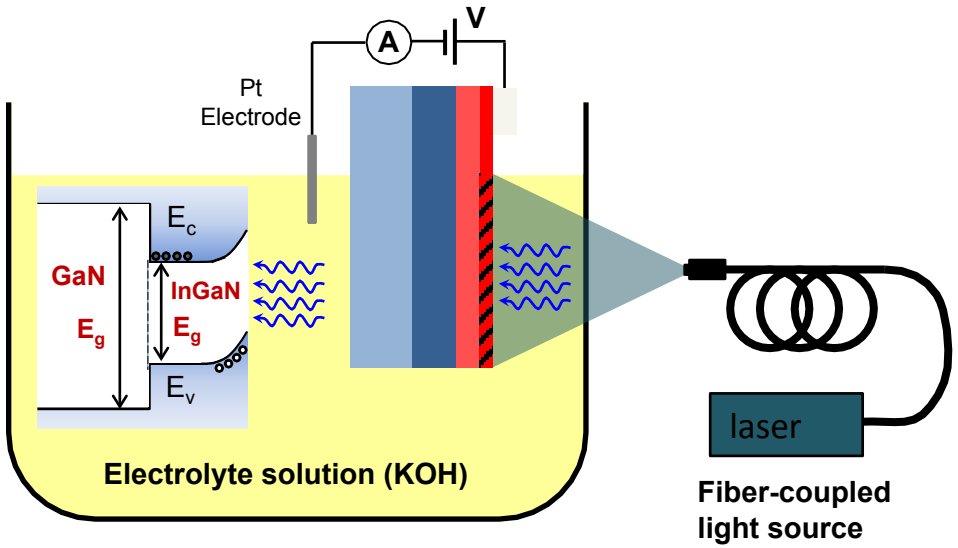
Nowak, A. K. et al.. Nat.com. **5**, 3240(2014)

Motivation for InGaN Quantum Dot SPS

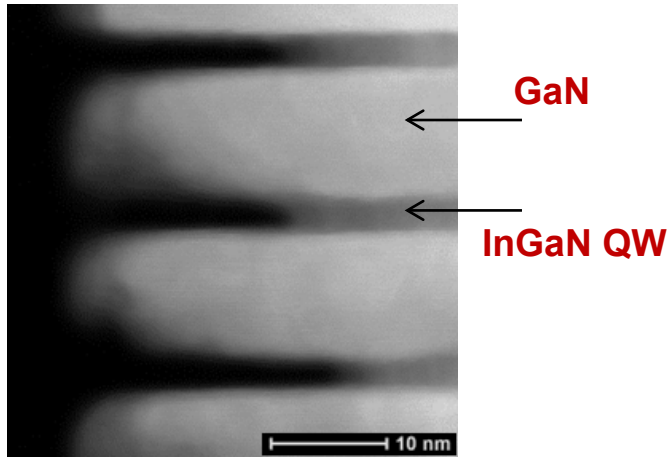
Room temperature, electrically-injected, chip-scale single photon source

- Large exciton binding energy so can enable room temp. operation
- Path to electrical-injection/chip-scale integration

- **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



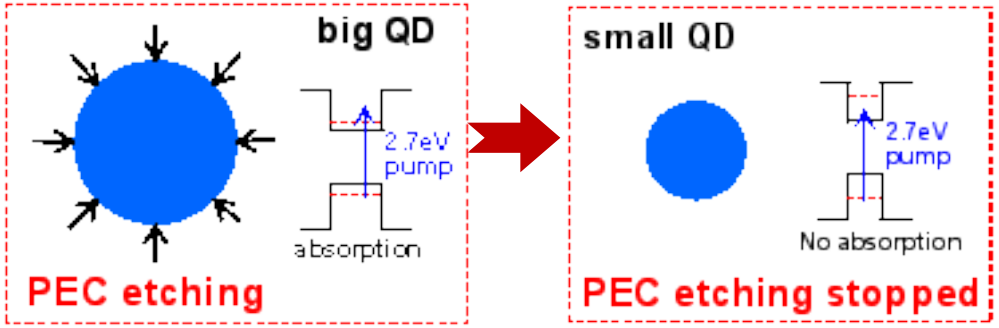
PEC etched InGaN/GaN QWS

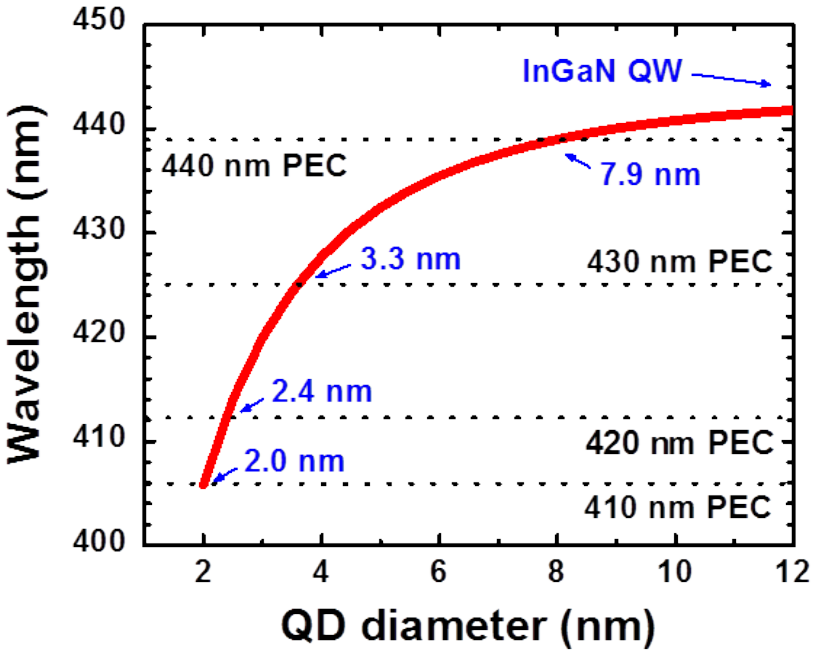


Fabrication of InGaN QDs via PEC etching

Quantum Size Control: Use size quantization to control QD size

Self-limiting PEC etch process:





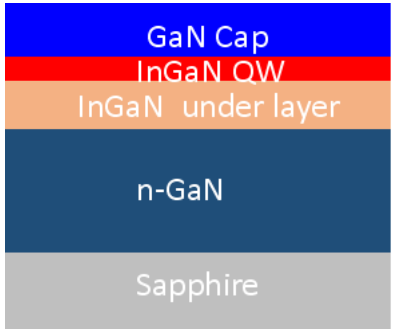
G. Pellegrini, et al., Journal of Applied Physics 97, 073706 (2005).

- 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
- Band gap selective
- QD size depends on PEC wavelength
- Monodisperse QD distributions ??

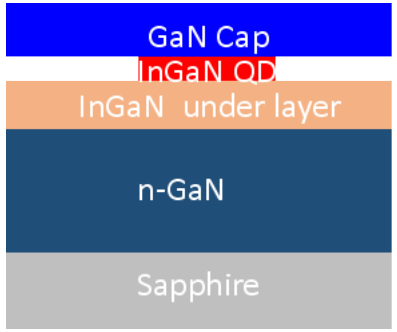
Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

Transmission Electron Microscope Images

Capped InGaN QW

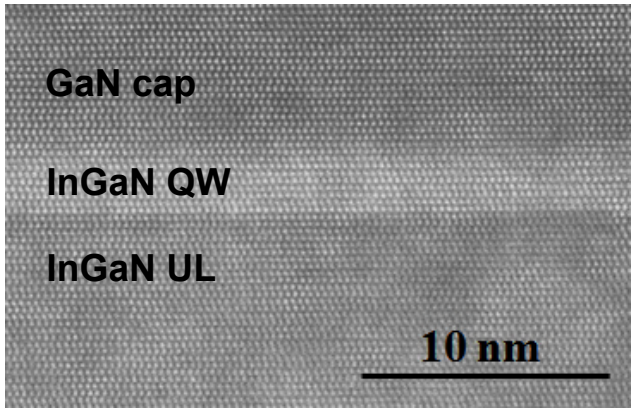


InGaN QD

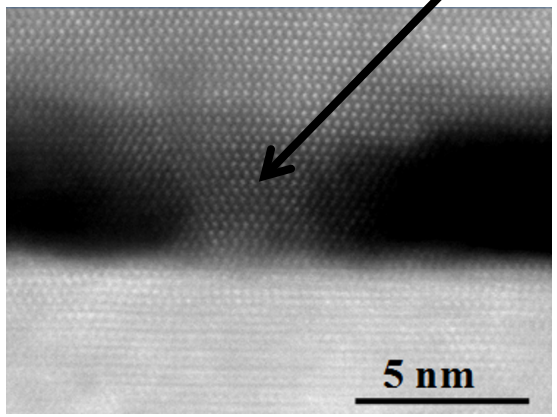


- High-angle annular dark-field (HAADF) TEM images
- Sample etched at 420 nm
- EDX mapping shows that dots are InGaN
- InGaN QDs are epitaxial to the underlying GaN
- 2% InGaN underlayer + GaN cap
- GaN cap provides partial passivation

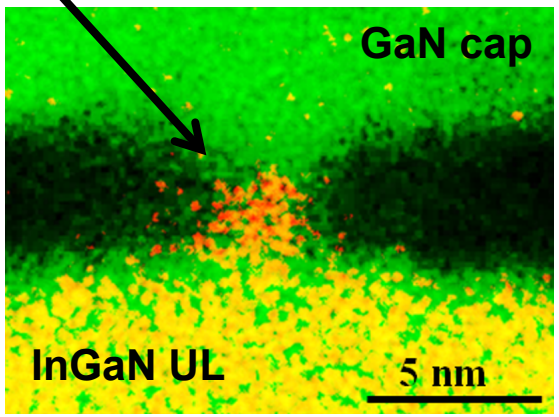
before PEC etch



after PEC etch



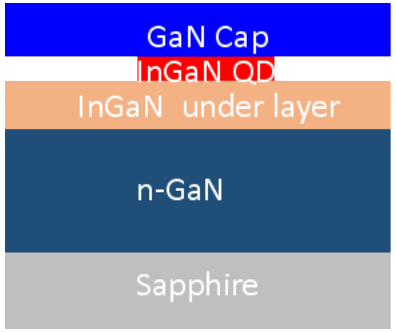
after PEC etch

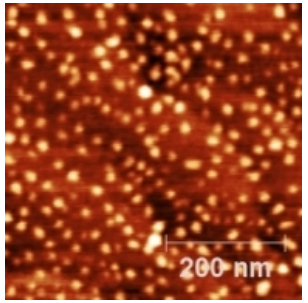


Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

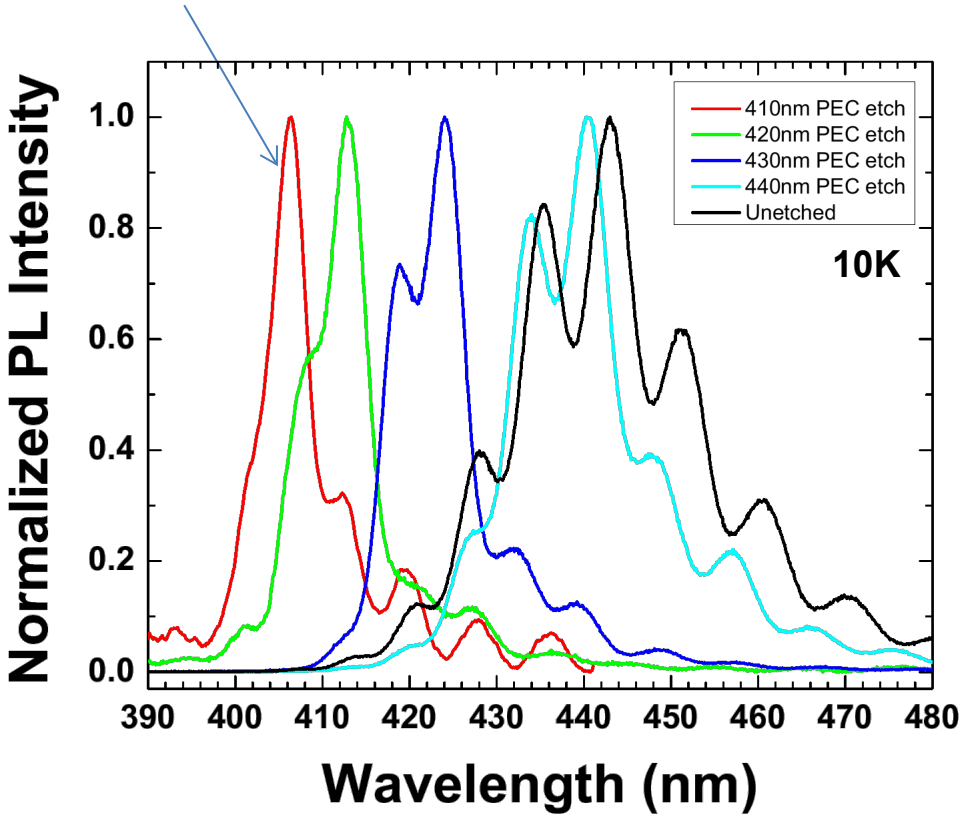
Photoluminescence from fabricated InGaN QDs

Capped InGaN QW





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



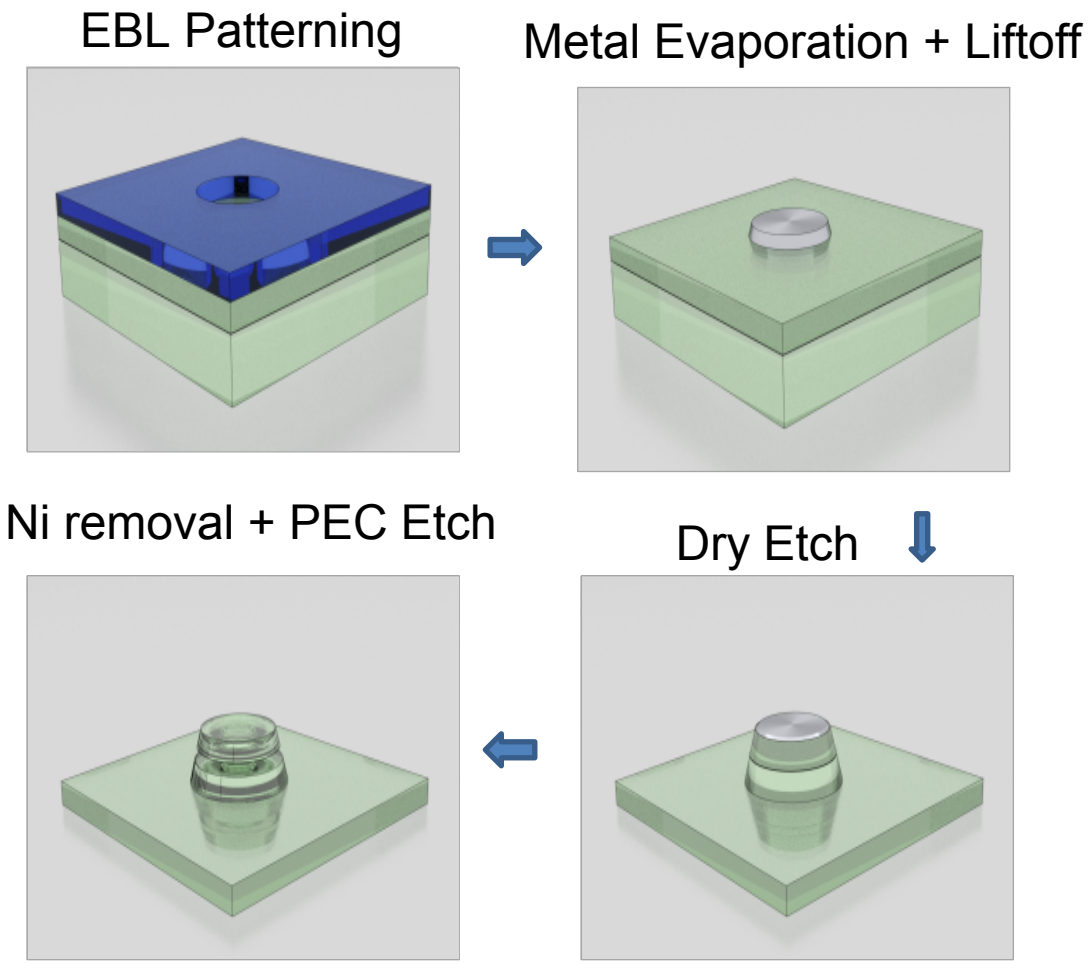
Photoluminescence (PL) data:

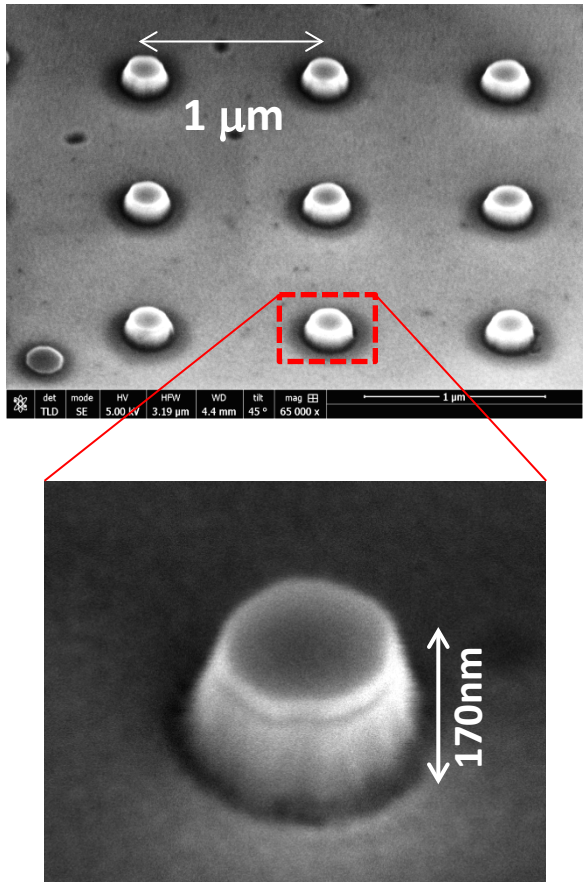
- **375 nm pump (ps pulsed)**
- **10K PL data**
- **PL wavelength determined by PEC etch wavelength**
- **PL linewidth: 24 nm → 6 nm**
- **Quantum size-controlled PEC etching works!**

Xiao, X. *et al.* Quantum-Size-Controlled Photoelectrochemical Fabrication of Epitaxial InGaN Quantum Dots. *Nano Lett.* **14**, 5616-5620, doi:10.1021/nl502151k (2014).

Patterned fabrication of InGaN QDs

- Deterministic placement



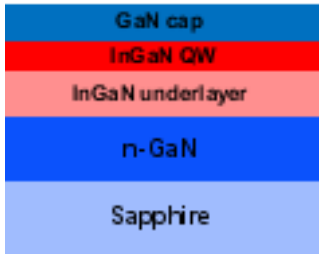


A. J. Fischer, P. D. Anderson, D. D. Koleske, and G. Subramania, ACS Photonics 4 (9), 2165 (2017).

PL from InGaN QDs

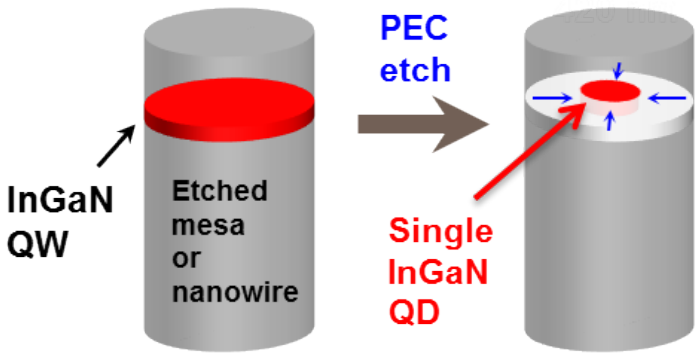
Sandia National Laboratories

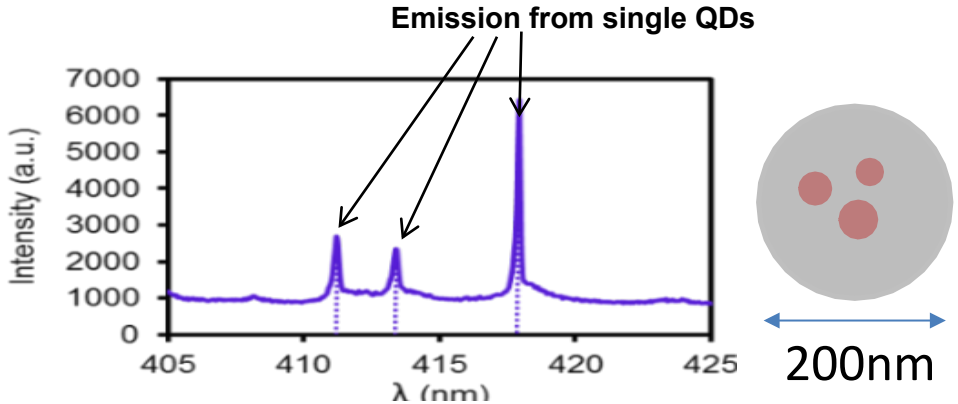
Capped InGaN QW

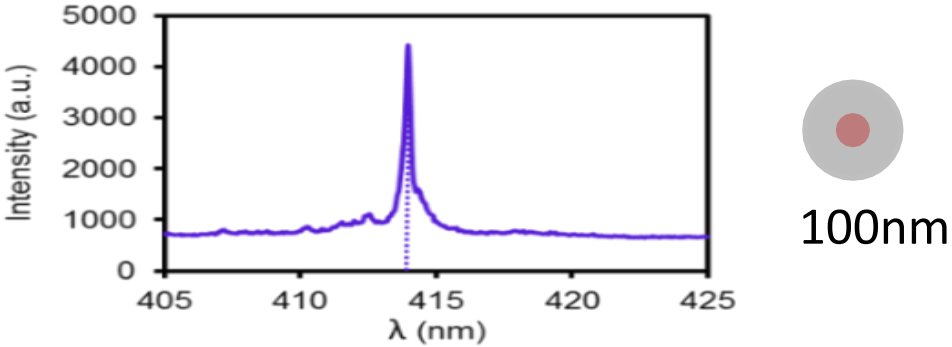


- Posts (100 – 200 nm) patterned with e-beam lithography
- Thicker GaN capping layer (~ 30 nm)
- Narrow PL emission (<1 nm FWHM) observed
- Better ratio of single QD mission to background

Fabrication of single InGaN QDs (methodology)



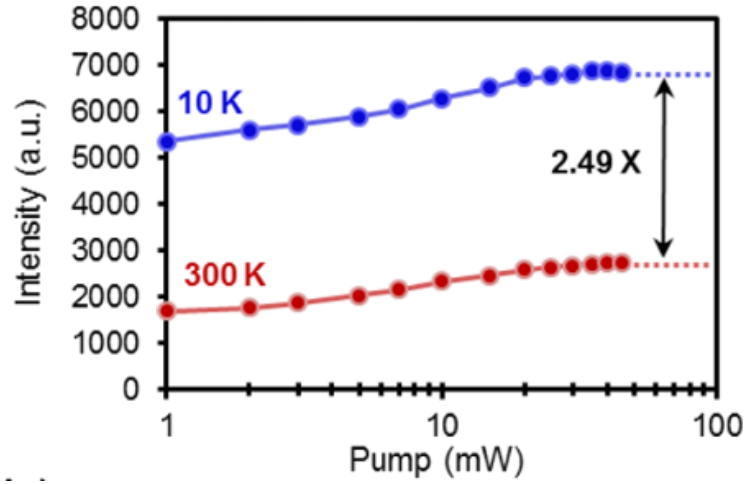




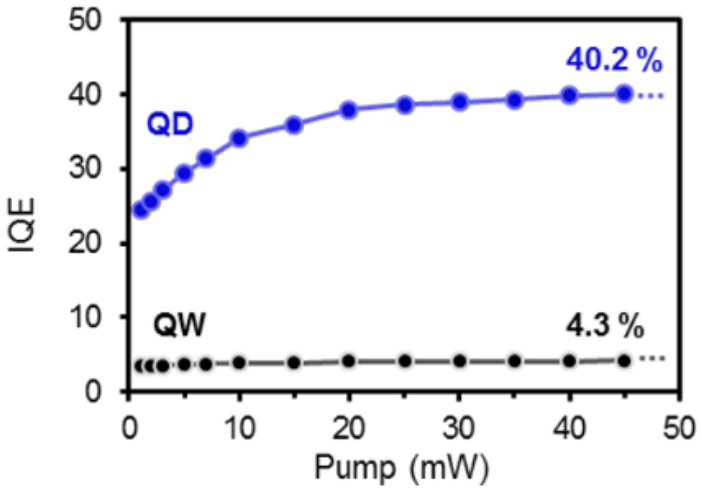
A. J. Fischer, P. D. Anderson, D. D. Koleske, and G. Subramania, ACS Photonics 4 (9), 2165 (2017).

IQE from InGaN QW vs QDs

QD PL pump dependence



IQE QD vs QW



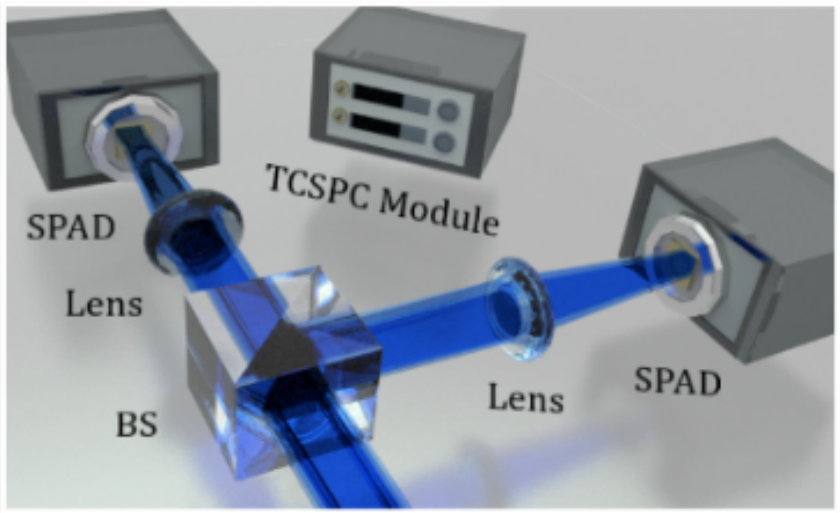
- Significant improvement in IQE between QW and QDs
- <u>Cause:</u> QDs are efficient emitters ; Also poor material etched away

A. J. Fischer, P. D. Anderson, D. D. Koleske, and G. Subramania, ACS Photonics 4 (9), 2165 (2017).

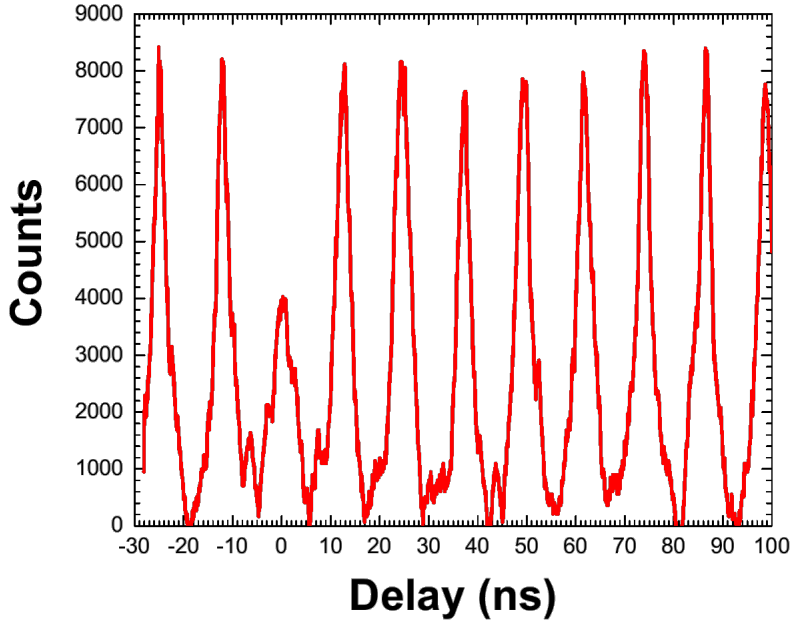
Single Photon Measurement: HBT experiment

- Observation of antibunching : g2 ~ 0.5 for PEC-etched InGaN QDs
- Ways to improve:
  - Thicker GaN cap
  - Reduce nanowire radius
  - Emission rate and light extraction enhancement (Incorporation into PhC)

HBT Experimental Set-up



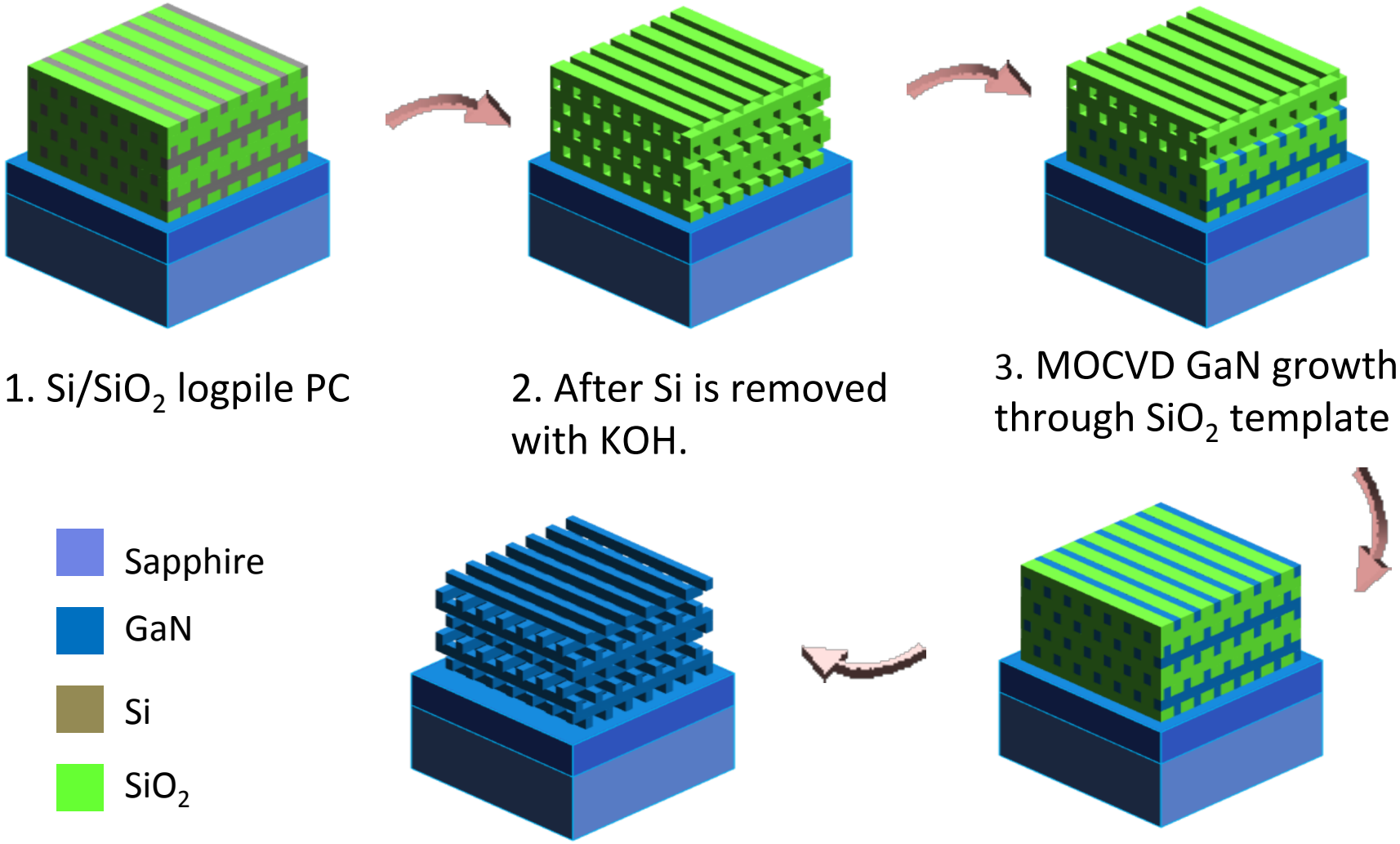
Pulsed g2 data



A. J. Fischer, P. D. Anderson, D. D. Koleske, and G. Subramania, ACS Photonics 4 (9), 2165 (2017).

GaN 3D Photonic crystals

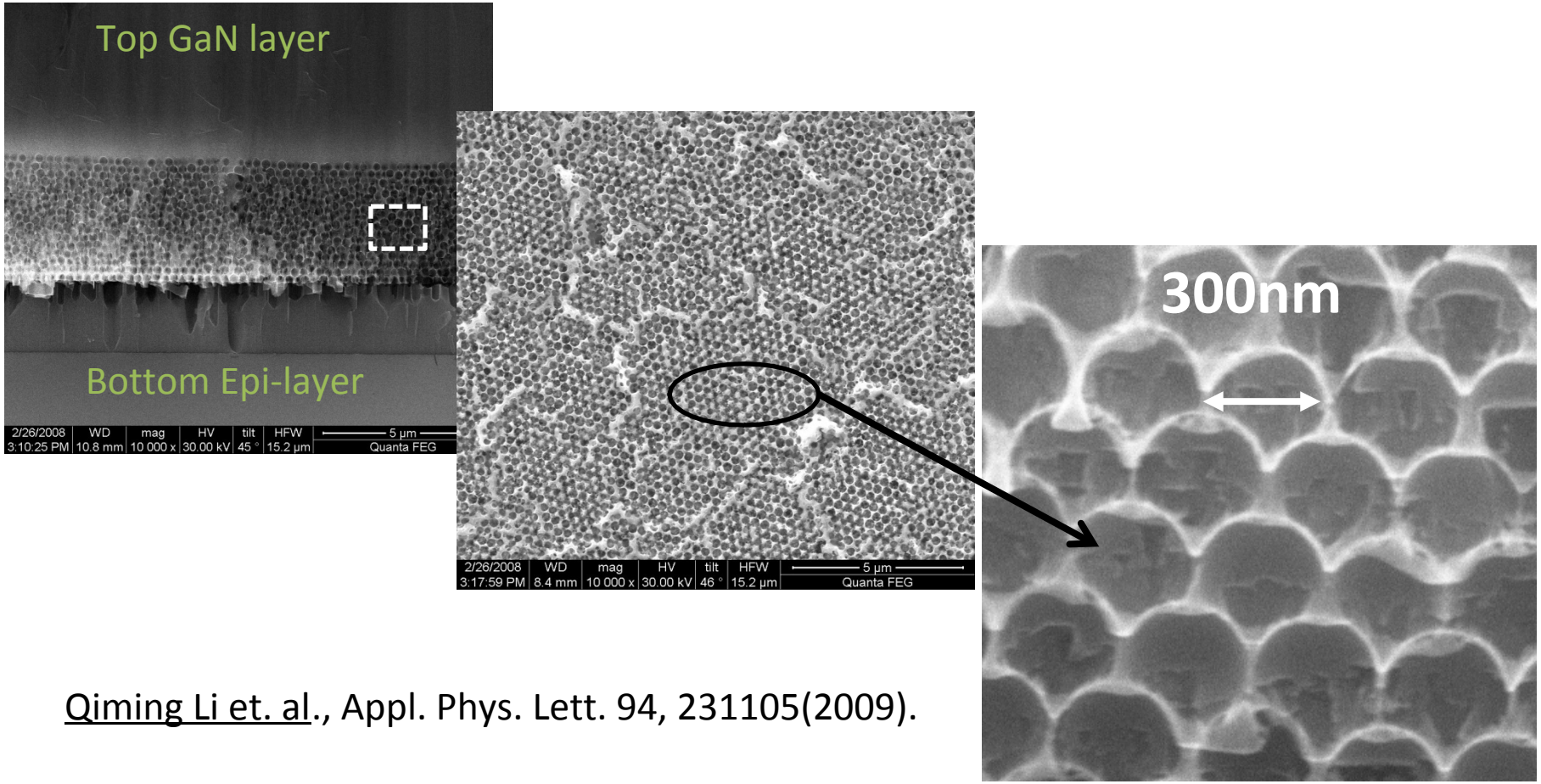
GaN growth through logpile template



G. Subramania, Q.Mi Li, Y-J Lee, J. J. Figiel, G. T. Wang, and A. J. Fischer, Nano Lett. 11 4591 (2011).

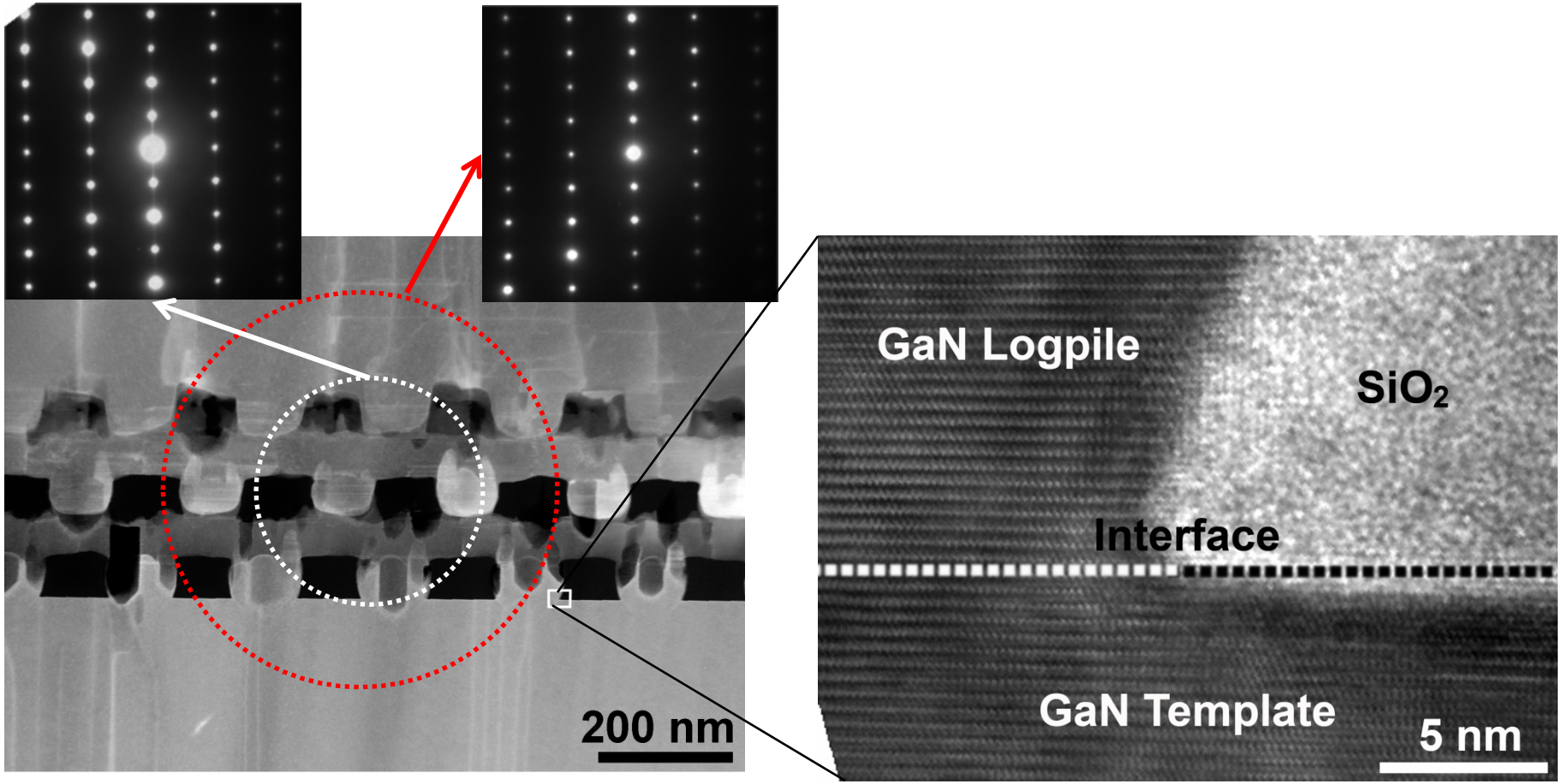
All GaN Logpile Photonic Crystal

Epitaxial GaN grown though nanostructured template reduces dislocation density



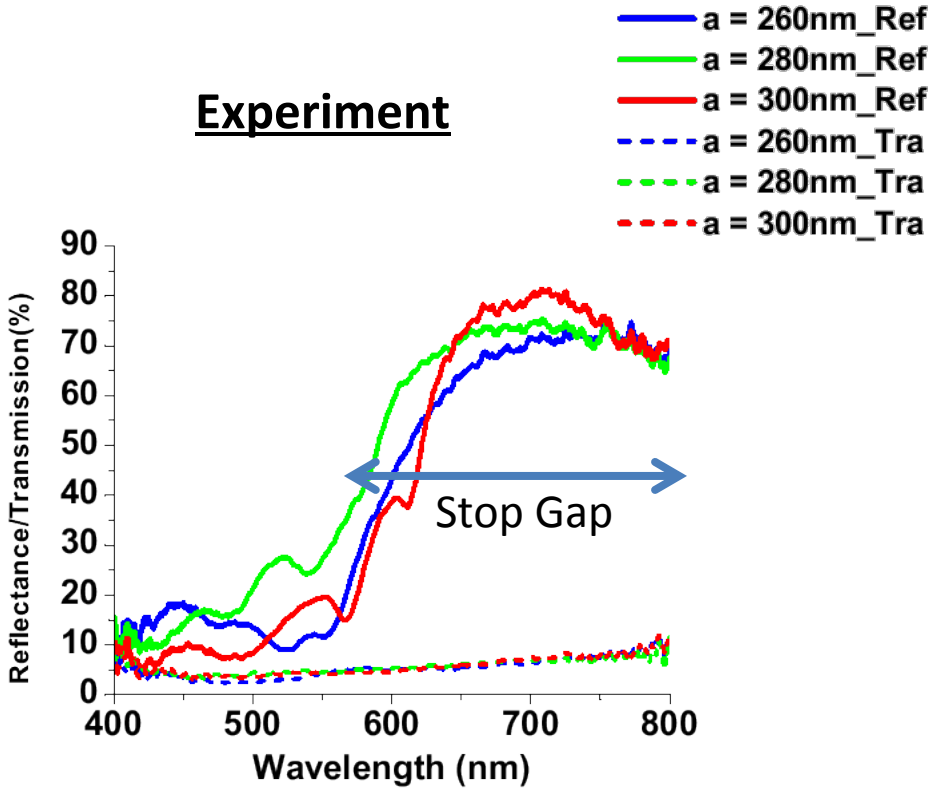
Qiming Li et. al., Appl. Phys. Lett. 94, 231105(2009).

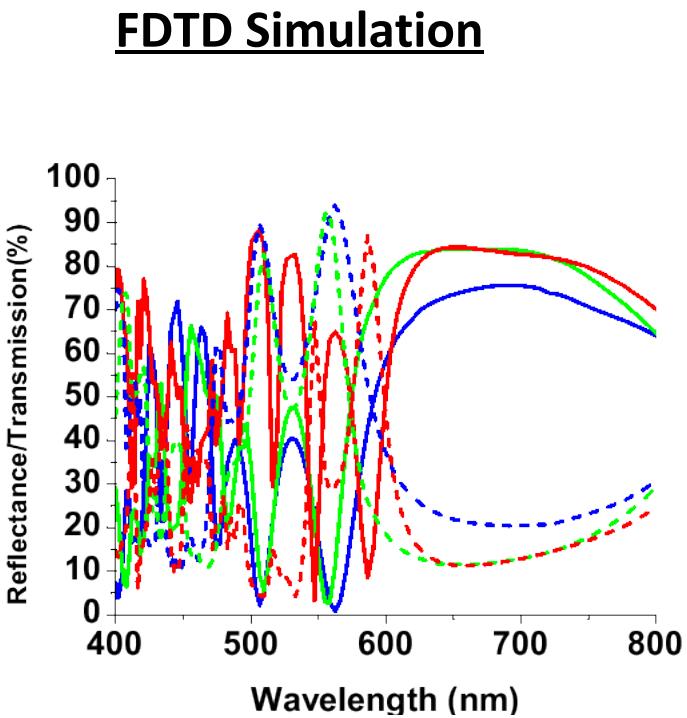
Bottom-up epitaxial growth of crystalline GaN



G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Optical Response



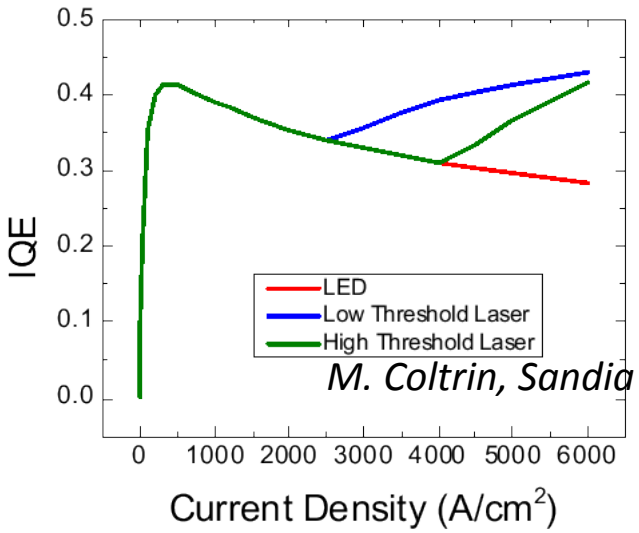


G. Subramania et. al. , Nano Lett. **11**, 4591 (2011).

Nanowire Photonic Crystal Lasers

(Jeremy B. Wright, Sheng Liu, Alexander Benz, George T. Wang, Qiming Li, Daniel D. Koleske, Ping Lu, Huiwen Xu, Luke Lester, Ting S. Luk, Igal Brener)

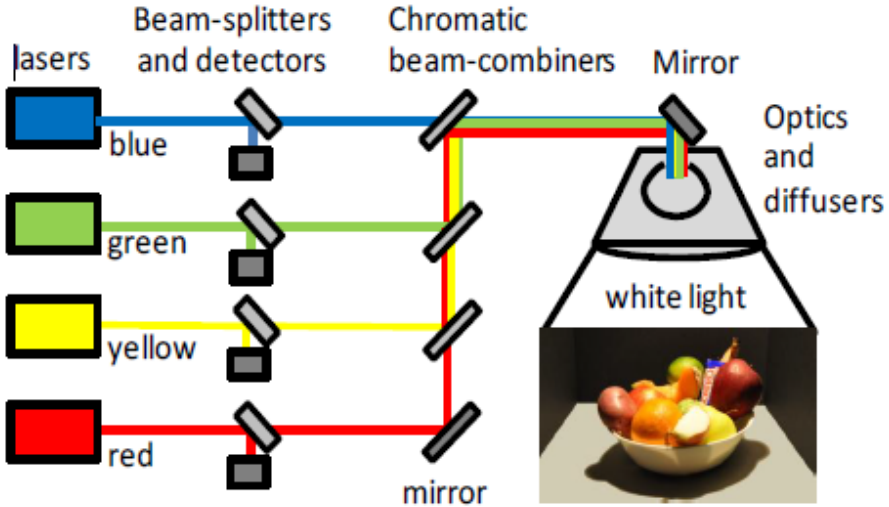
Why Lasers in Solid State Lighting?



The LED "efficiency droop" problem:

- ***InGaN LEDs exhibit a decrease in efficiency at high drive currents***
- ***limits the operating current density***
- ***increases the cost per lumen***

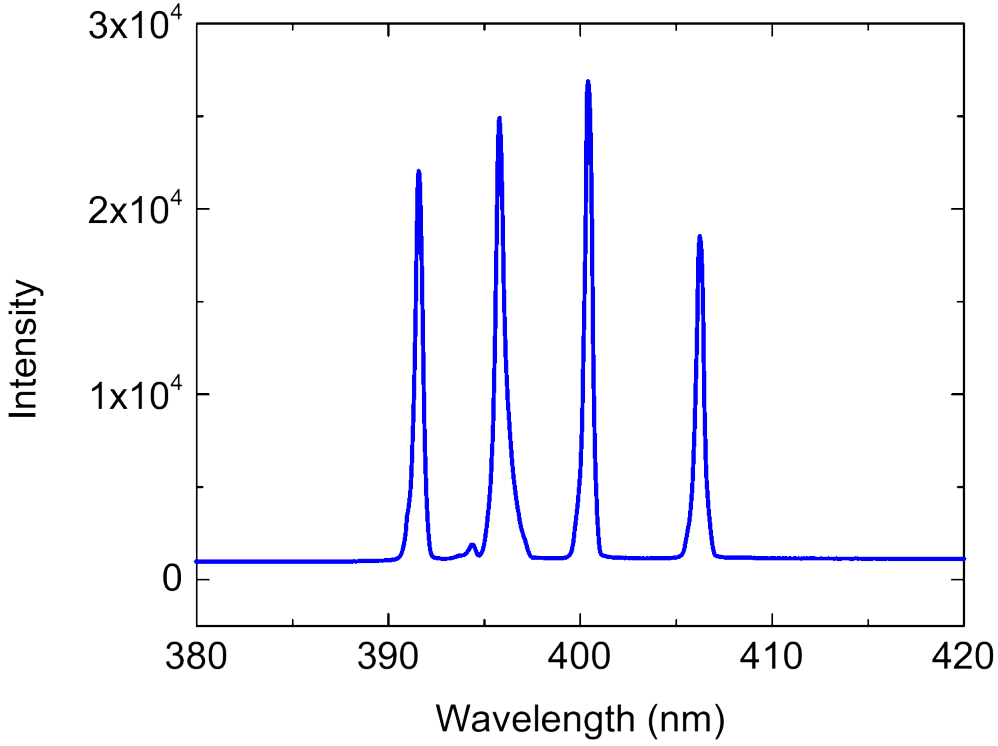
- ***4 color lasers suitably combined can achieve high color rendering***
- ***Lasers can potentially mitigate the efficiency droop problem !***

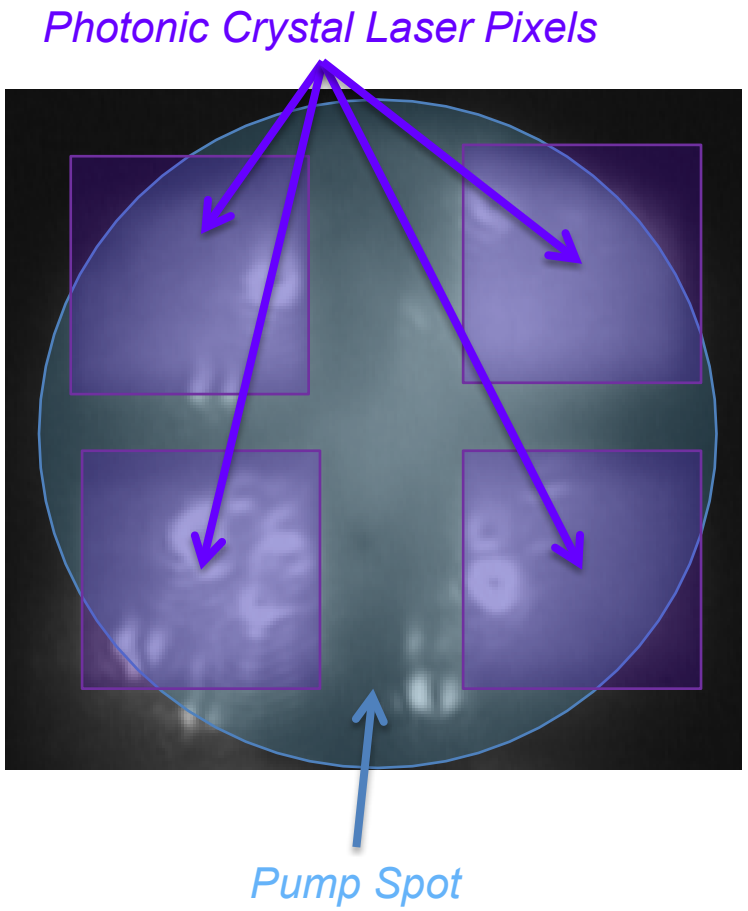


A. Neumann et al., "Four-color laser white illuminant demonstrating high color-rendering quality," Opt. Express, vol. 19, pp. A982-A990, 2011.

Multiple Laser Pixels Coexcited

Emission from 4 adjacent laser pixels.



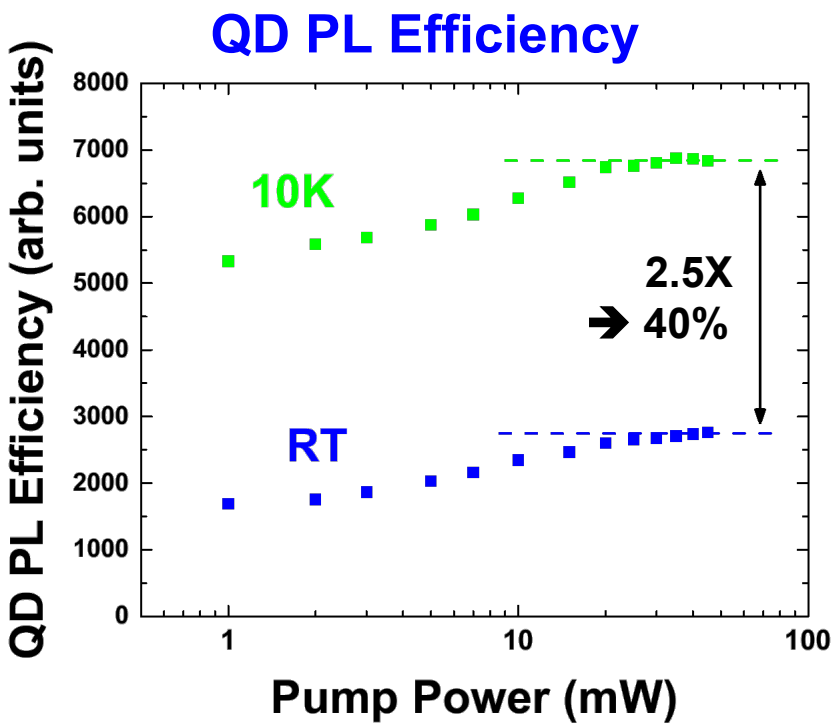


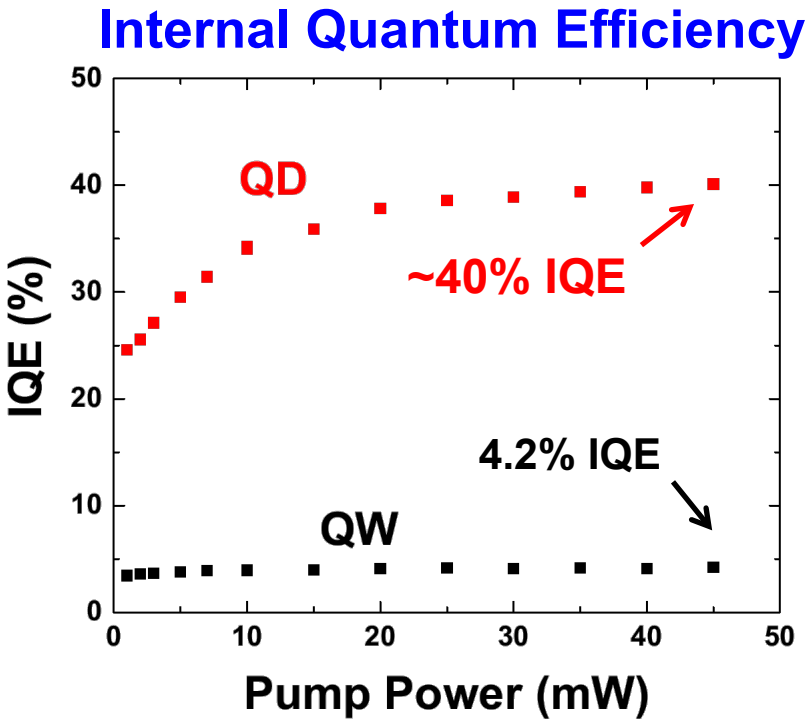
Wright, J. B. *et al.* Multi-Colour Nanowire Photonic Crystal Laser Pixels. *Sci. Rep.* **3**, 2982, doi:10.1038/srep02982

InGaN QD internal quantum efficiency

Capped InGaN QW

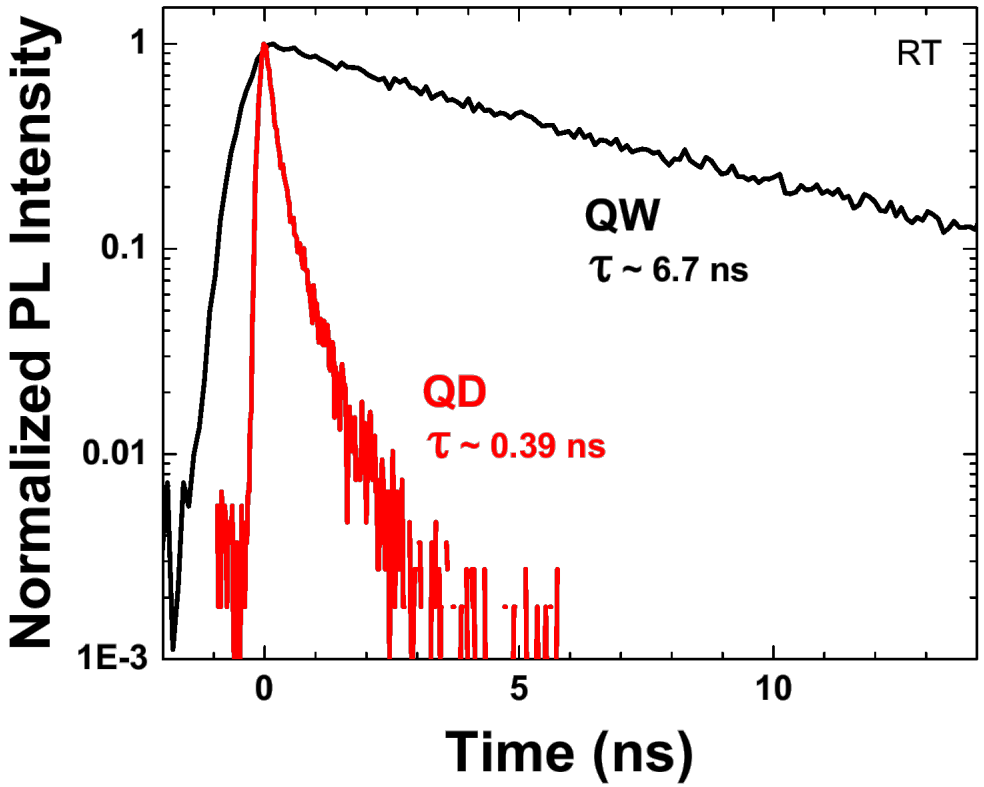
- Compare 10K and RT PL efficiency
- Assumes 10K PL is 100% efficient
- PL Intensity drops by >100X after QD etching
- IQE goes up by almost 10X after QD etching
- QDs are expected to have better IQE





Time-resolved PL data from InGaN QDs

Capped InGaN QW



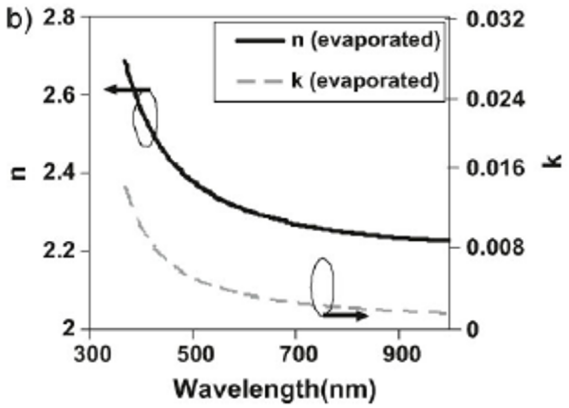
TRPL data:

- 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 → QDs

Visible Frequency Logpile Photonic Crystal

Sandia National Laboratories

Choice : TiO_2



Requirements:

- **High enough index with low loss in the visible :**
  - n ~ 2.3-2.4 in the visible /w k< 0.015
- **Easy to deposit :**
  - Sputtering, evaporation, solgel, Atomic Layer Deposition

Band Structure Calculation

Solve Electromagnetic wave equation for Plane wave

$$\begin{cases} E(r,t) \propto e^{-i\omega t} \\ H(r,t) \propto e^{-i\omega t} \end{cases}$$

$$\boxed{\nabla \times \left(\frac{1}{\varepsilon(\boldsymbol{r})} \nabla \times \boldsymbol{H}(\boldsymbol{r}) \right) = \left(\frac{\omega}{c} \right)^2 \boldsymbol{H}(\boldsymbol{r})}$$

In a periodic potential

$$\varepsilon(\boldsymbol{r} + \boldsymbol{R}) = \varepsilon(\boldsymbol{r})$$

$$\boldsymbol{R} = a_1\hat{x} + a_2\hat{y} + a_3\hat{z}$$

Apply Bloch's Theorem

$$E, H(r + R) = E, H(r)$$

Plane Wave Expansion Method

Reciprocal (K) space

Reciprocal Lattice vector

$$\varepsilon(r) = \sum_G \bar{\varepsilon}(G) e^{iG.r} \qquad E,H(r) = \sum_G \bar{E},\bar{H}(G) e^{-i(-k+G).r} \qquad G \cdot R = 2\pi n$$

Bloch Waves $\bar{H}(G) = H_x(G)\hat{x} + H_y(G)\hat{y} + H_z(G)\hat{z}$

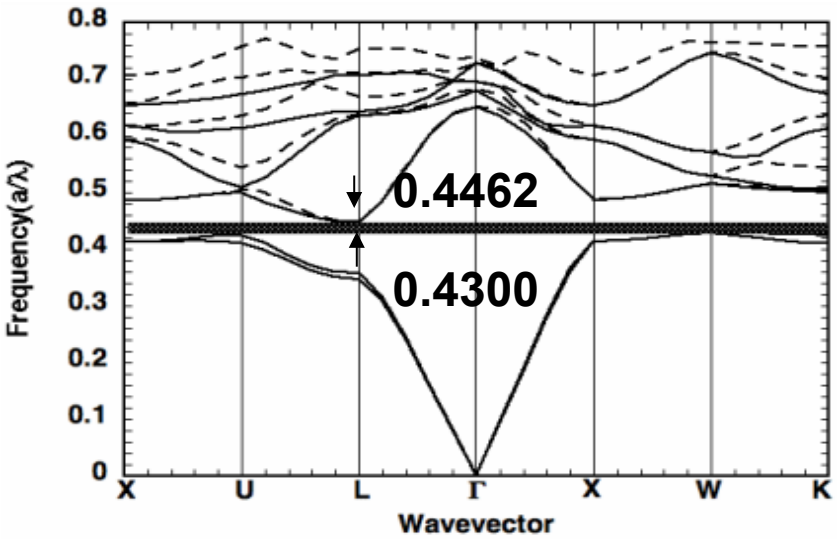
Eigen value equation

$$\nabla \times \left(\frac{1}{\varepsilon(r)} \nabla \times H(r) \right) = \left(\frac{\omega}{c} \right)^2 H(r) \quad \Rightarrow \quad \boxed{A\bar{H}_n(k) = -\frac{a^2 \omega_n^2}{c^2} \bar{H}_n(k)}$$

Band index

Wave vector within the first BZ

Photonic Band Structure for TiO_2 logpile



1st BZ

U

W

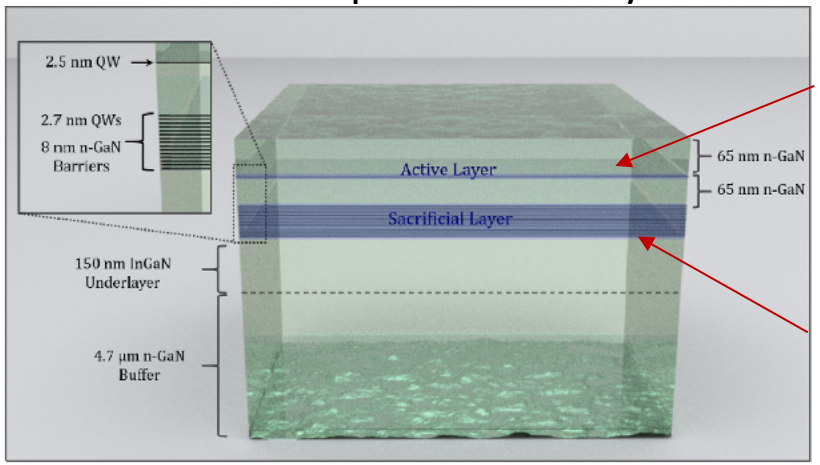
Eigen value equation becomes a matrix equation for which you can write a code and solve for band structure within the first Brillouin zone.

- **n ~ 2.3**
- **4% bandgap**
- **~ 20nm @ 500nm**

Example: InGaN/GaN based membrane Photonic Crystal

- Photoelectrochemical (PEC) etching of a sacrificial InGaN layer

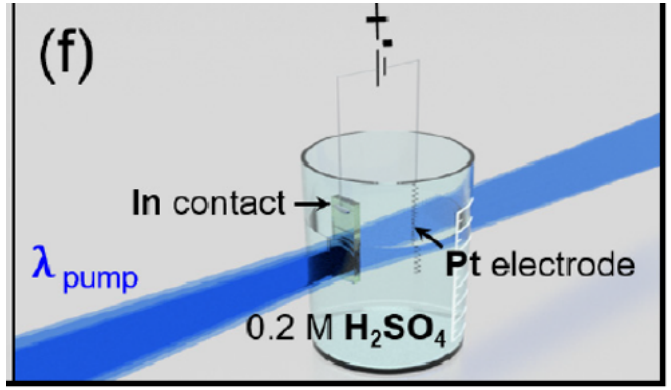
Epitaxial film layout



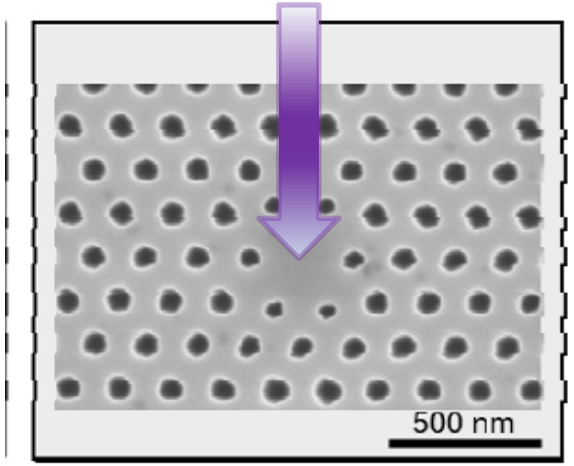
InGaN SQW
low indium

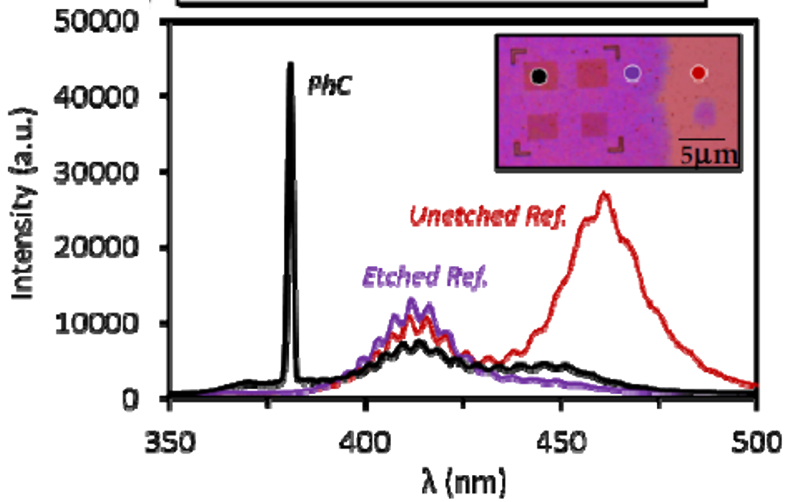
InGaN MQW
higher indium
sacrificial layer

Photoelectrochemical etch



pump



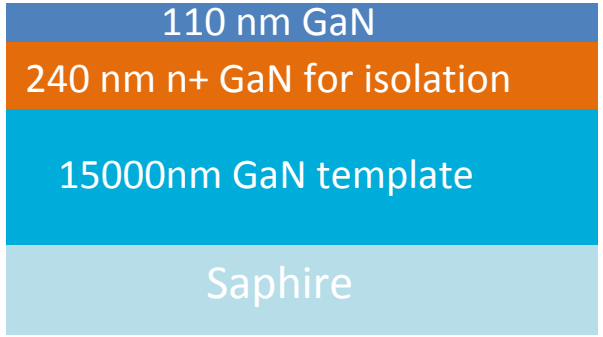


- The epitaxial structure contains a low *In* concentration active layer for PhC membrane
- Higher *In* concentration InGaN/GaN MQW is grown between the bottom substrate
- InGaN layer is etched away using PEC to create a low index layer

Approach is challenging and harder for thicker MQW layer

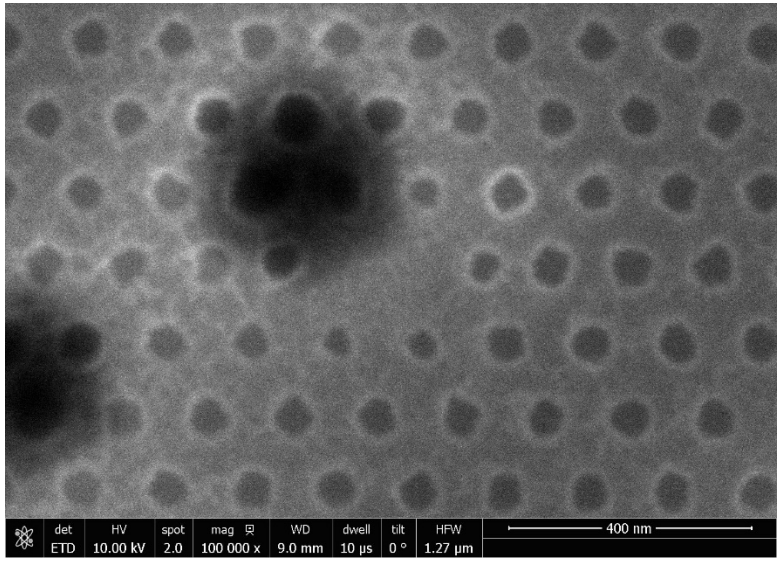
Figures reprinted/adapted from Anderson, P. D.; Fischer, A. J.; Koleske, D. D.; Gunning, B. P.; Subramania, G., *Optical Materials Express* **2018, *8*** pp3543-3550.; Copyright 2018 OSA.

PhC Membrane Fabrication with EC Etch

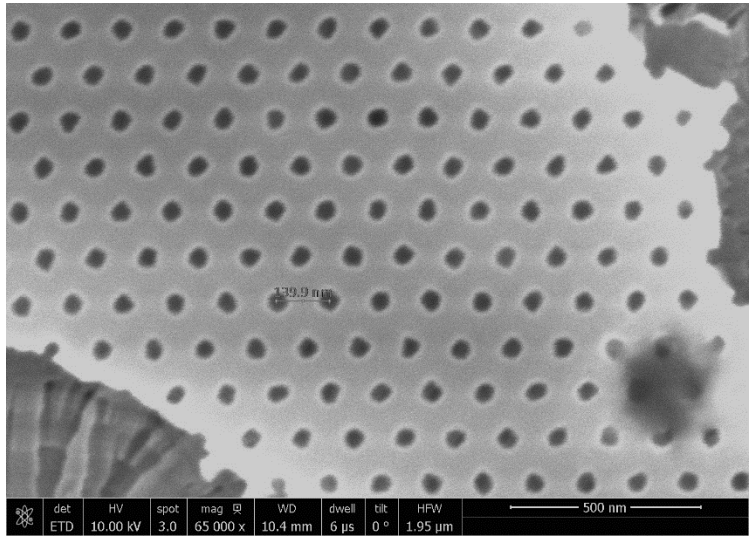


- Follow similar fabrication procedure to form PhC like before till cladding removal step
- EC etch highly doped cladding region

Pre –EC Etch



Post –EC Etch



EC etched region revealing GaN template