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Nanostructured Isolation Layer for Enhanced III-Nitride Photonics Performance

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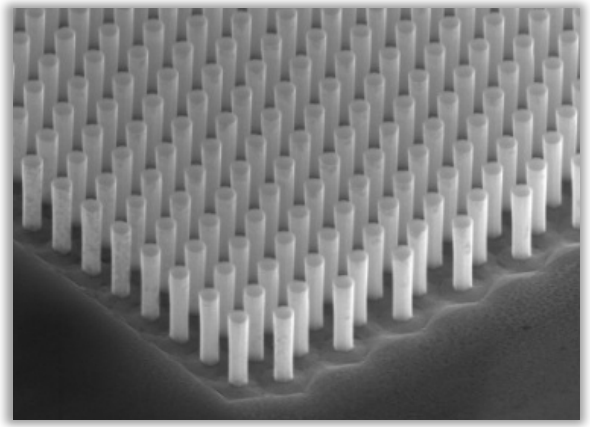

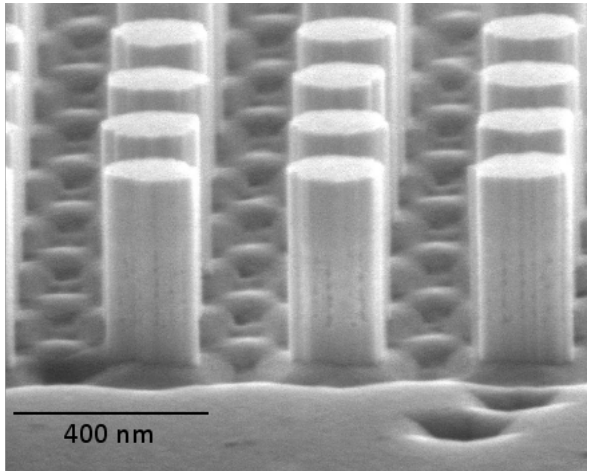

MRS Fall 2022, Boston, MA

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Outline

- Brief intro on scattering
- Huygen's Metasurface
- III-Nitrides for Metasurfaces
  - Low index substrate isolation : fabrication and measurement

Scattering

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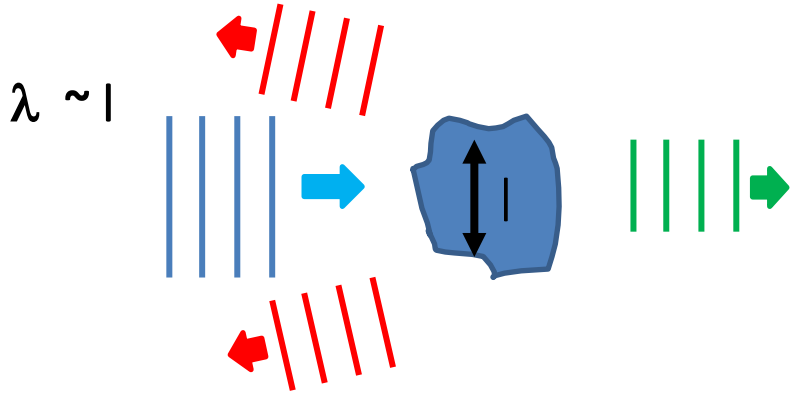
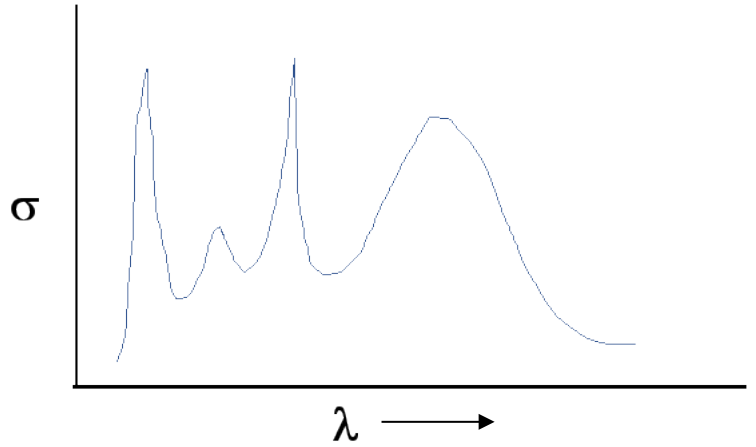
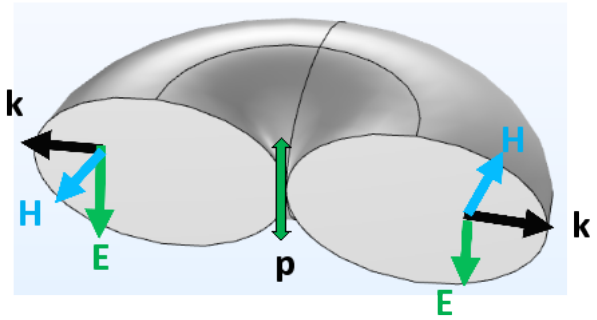
Mie scattering

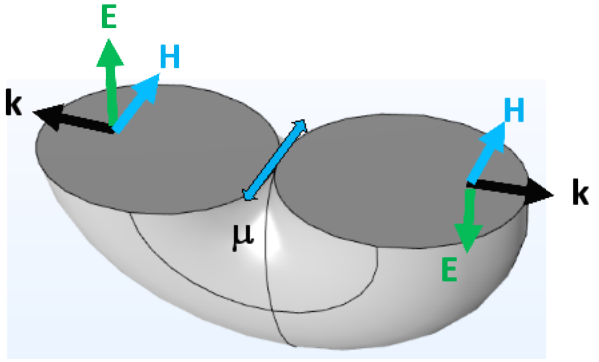




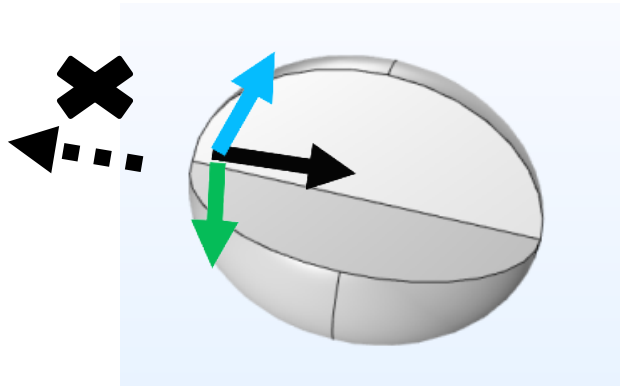
Crossed Electric and Magnetic dipole emission



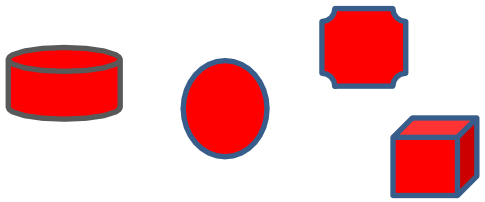
Electric dipole emission



Magnetic dipole emission



Only forward scattering (no backward)



Different particle shape their refractive index and backround index can affect scattering response

Huygen's Metasurface Design

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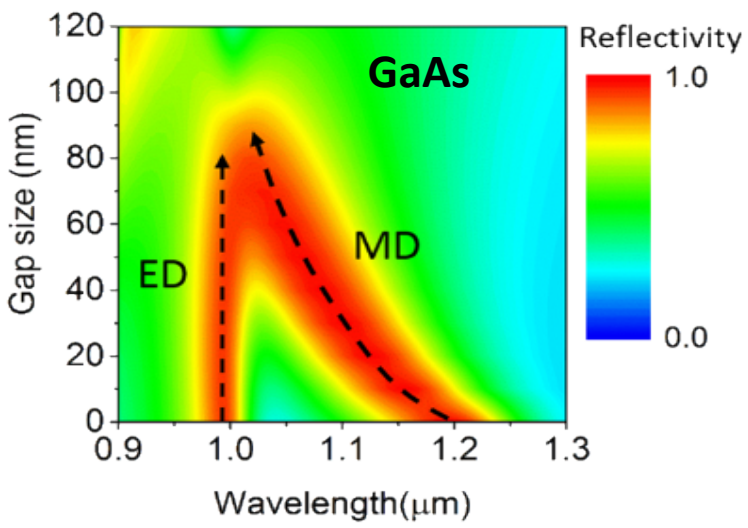
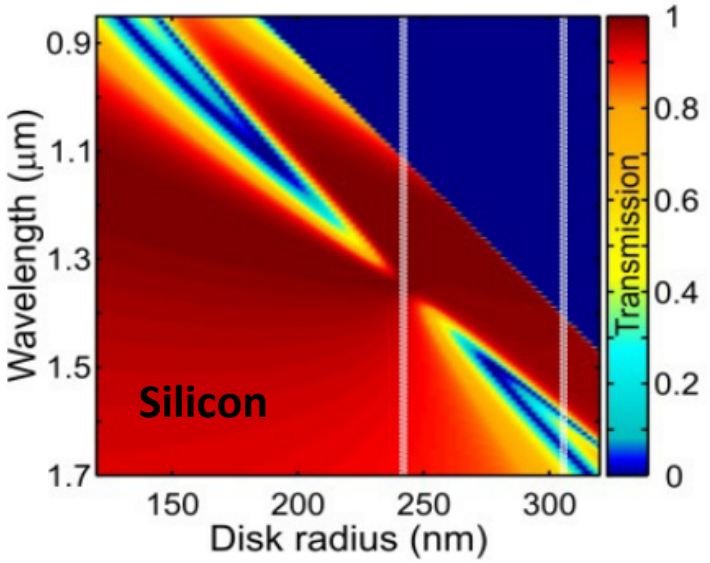
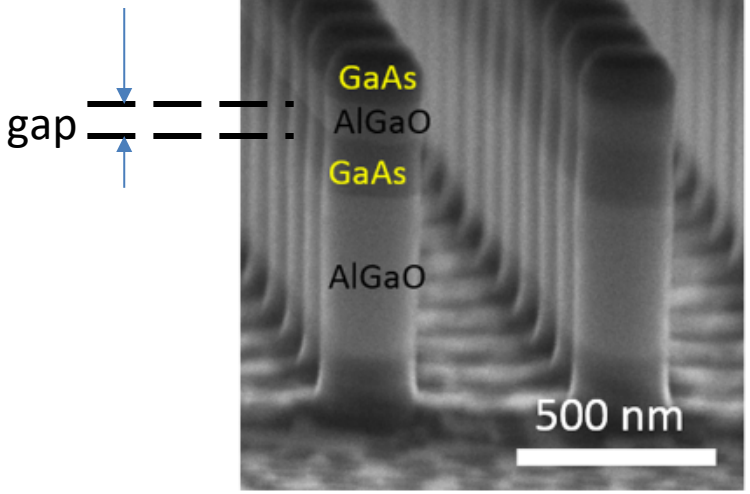
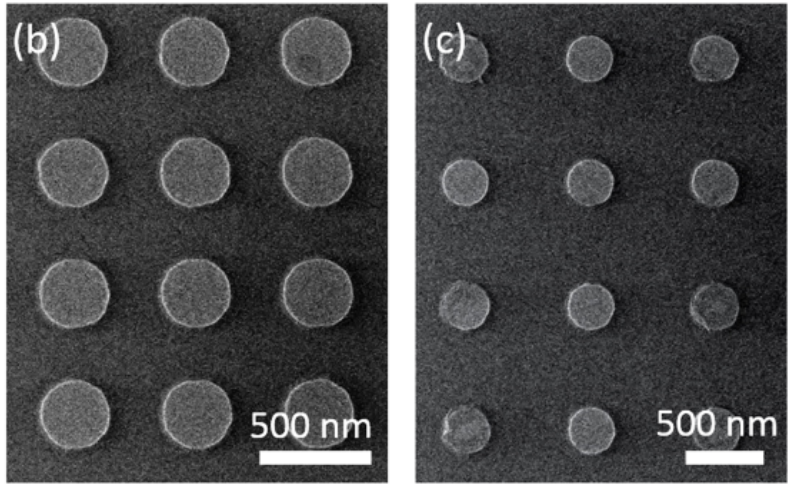
Full Transmission





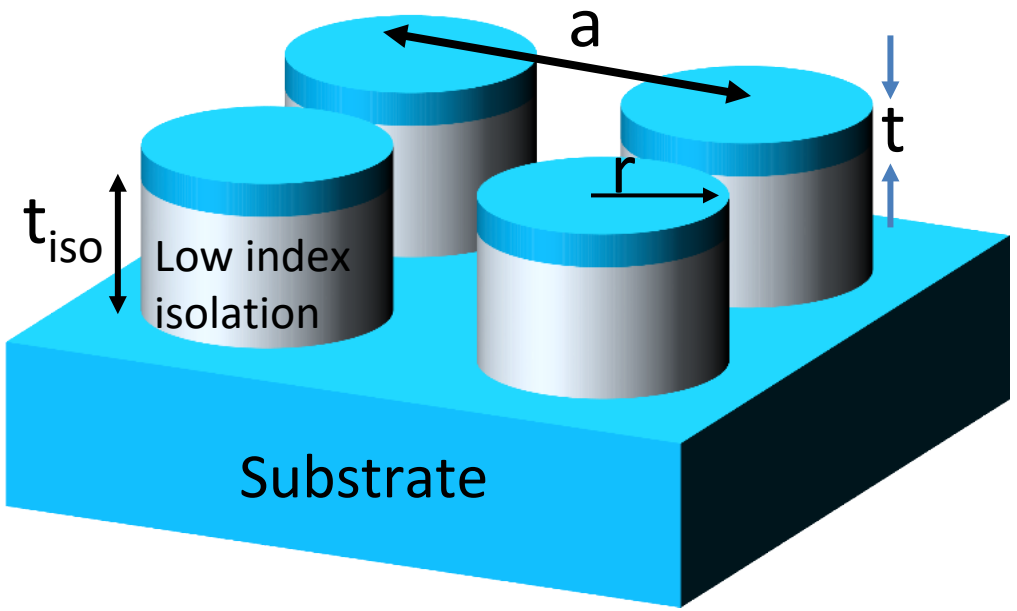
Si Resonator Index = 3.5
Ambient Index = 1.6



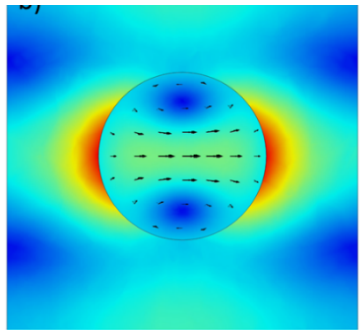


Figures adapted from: Decker, M. Adv. Opt. Mat. 3,6 (2015), Liu, S. Nano Lett. 16.9: 5426, (2016), Liu, S. Nano Lett. 2017, 17, 4297−4303

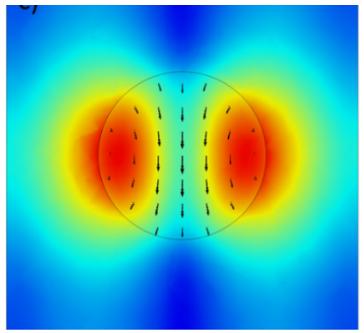
Huygen's Metasurface Design

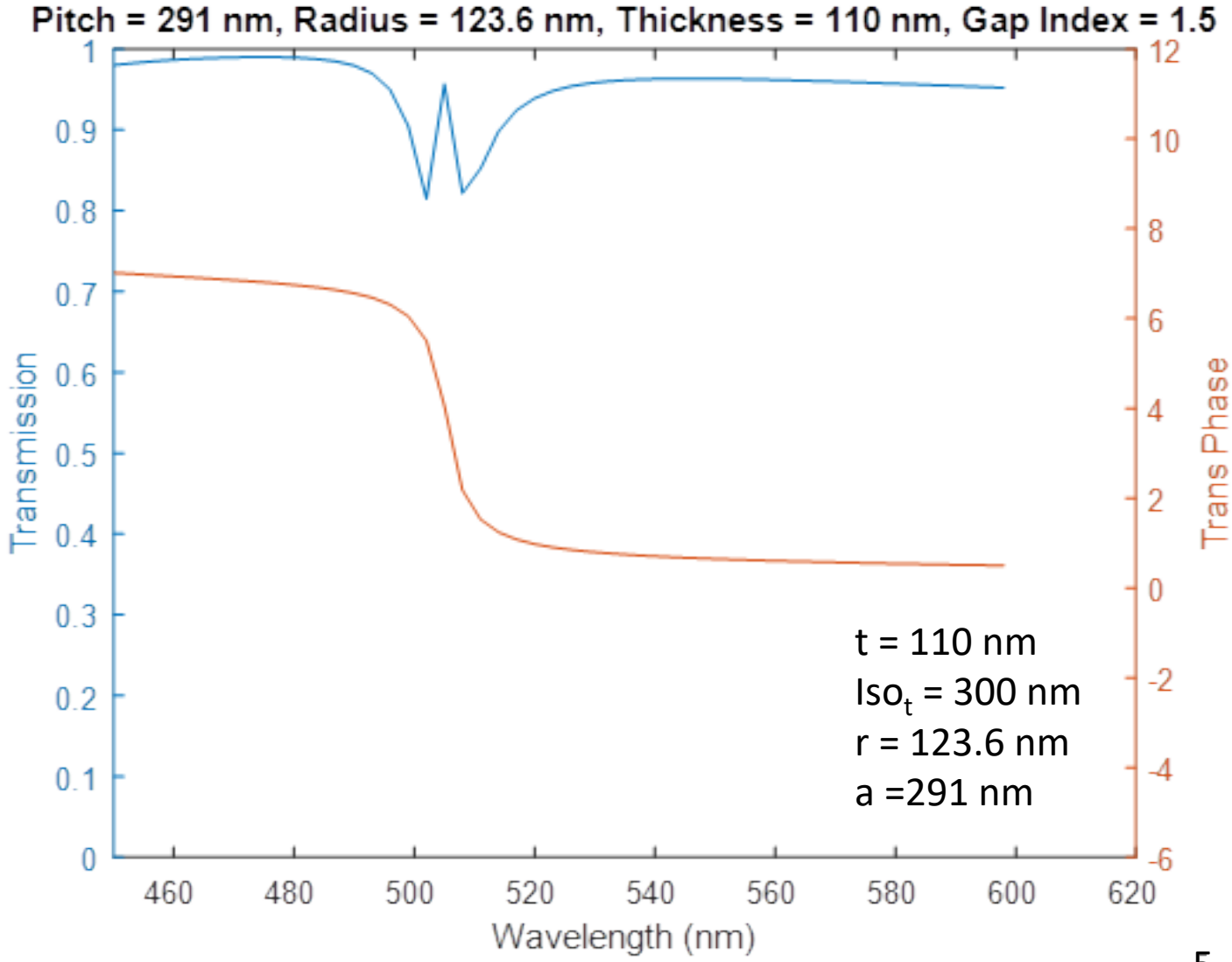


Electric dipole



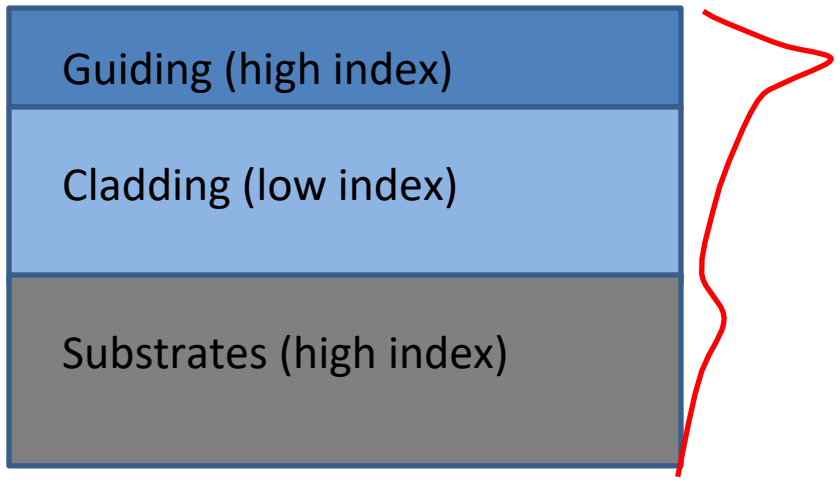
Magnetic dipole



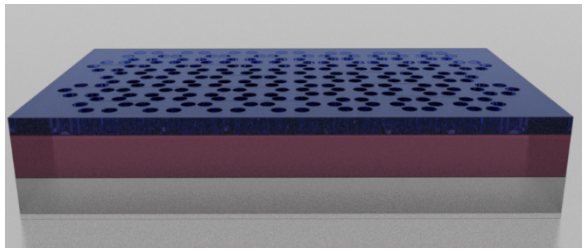


Photonic Devices and Substrate Isolation

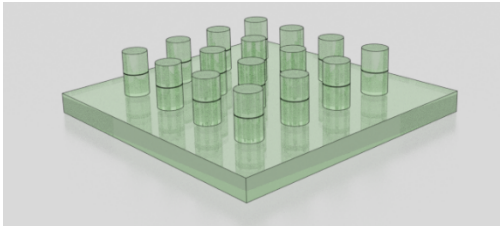
- Nanophotonic devices need isolation from a high index substrates/template
  - Electromagnetic field confined to the active or light guiding layer
  - Low index cladding layer (n ~ 1 – 1.6)
  - Important for photonic crystal or metasurface based devices
  - Optimal advantage of photonic band structure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

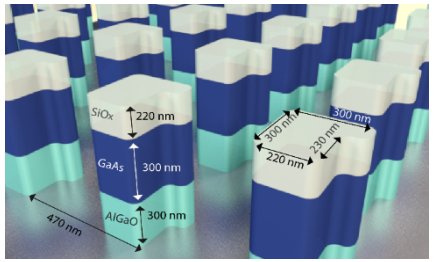


Hole array PhC



Nanowire PhC

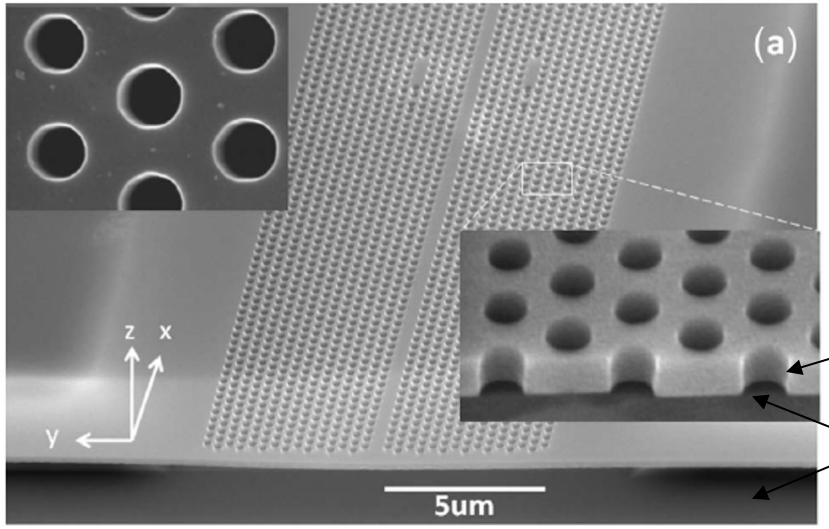




Metasurface

Hole-Array Photonic Crystals

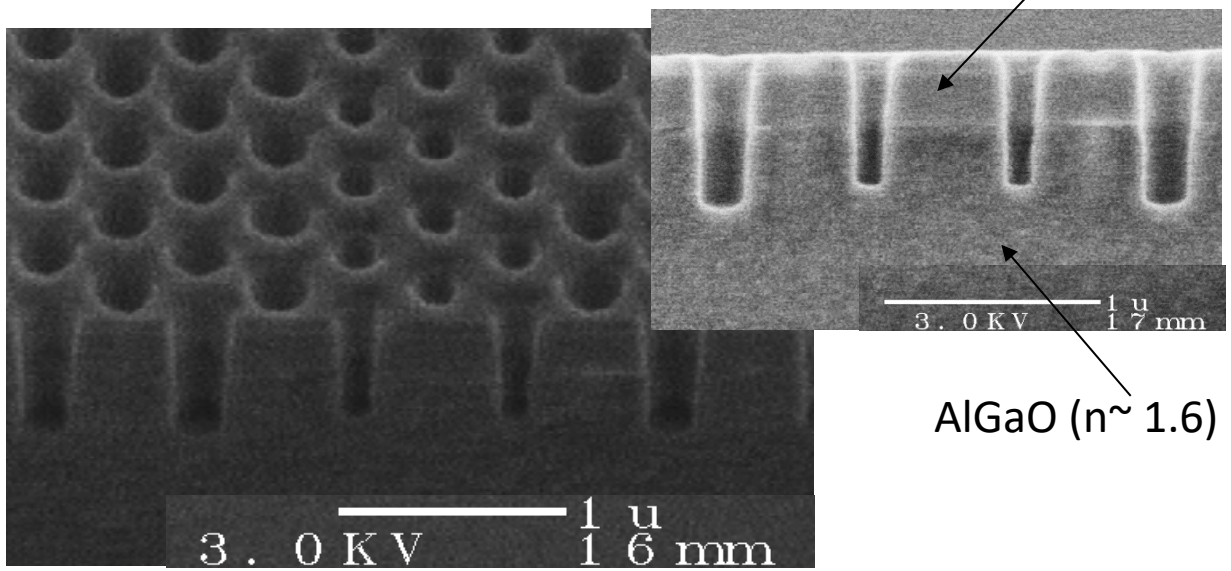
SOI based PhC



Si (n~ 3.4)

Air

GaAs/AlGaAs based PhC



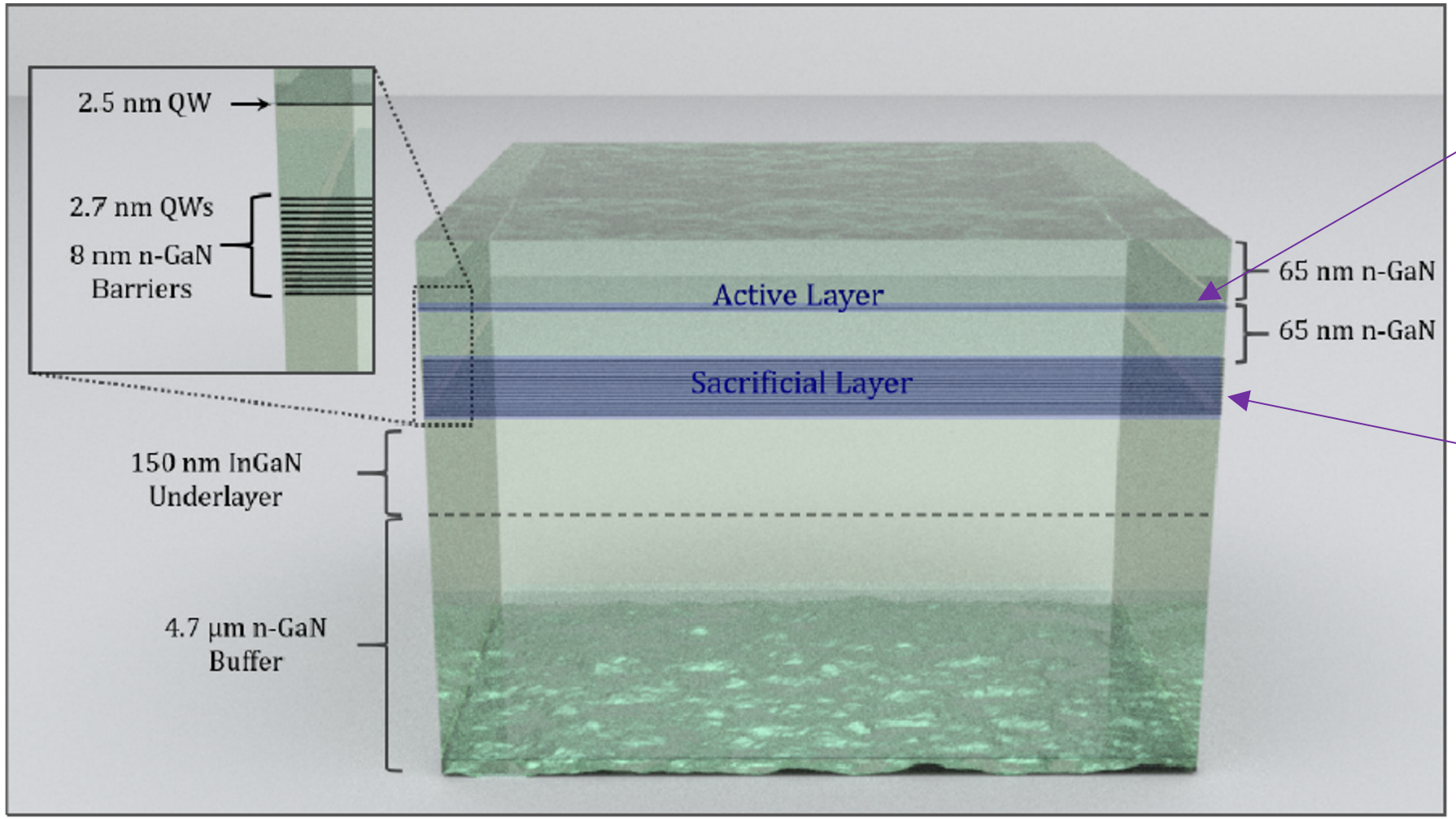
GaAs (n~ 3.4)

AlGaO (n~ 1.6)

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

- 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**

III-Nitride Membrane PhC : One approach



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

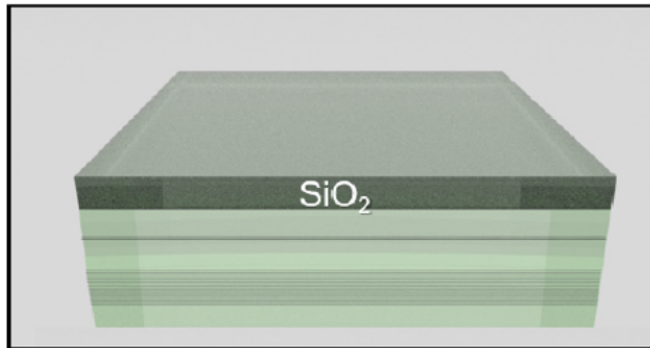
InGaN MQW higher Indium (**16%**) sacrificial layer

Epi Structure with a bottom sacrificial MQW layer

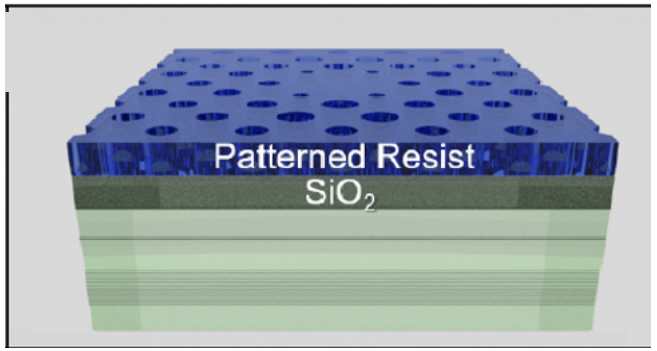
Figures reprinted/adapted from Anderson, P. D.; Fischer, A. J.; Koleske, D. D.; Gunning, B. P.; Subramania, G., *Optical Materials Express* **2018, *8*** pp3543-3550.; Copyright 2018 OSA.

Fabrication steps

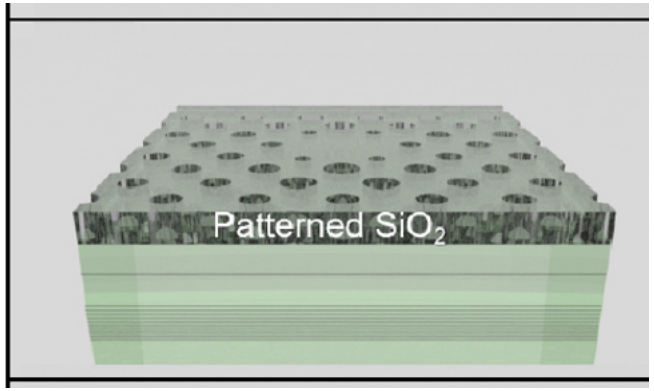
Deposit SiO_2 hardmask



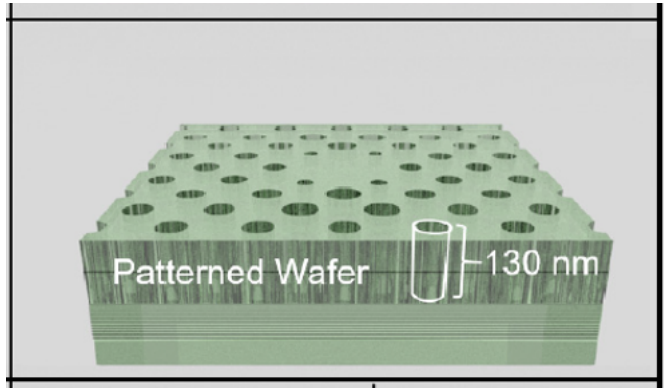
EBL pattern in PMMA



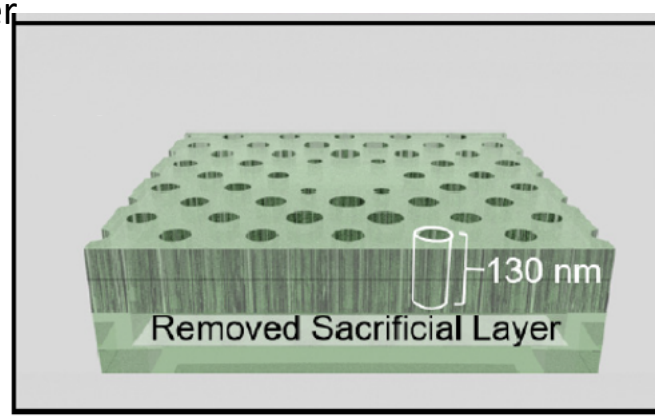
Etch Hardmask



Etch III-nitride active layer through patterned hardmask



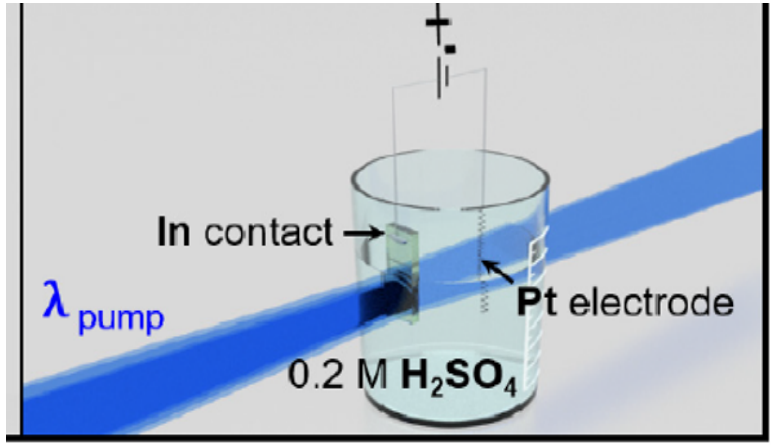
Remove sacrificial multiquantum well layer

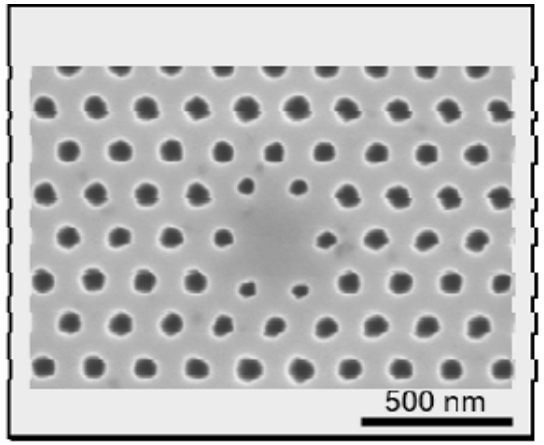


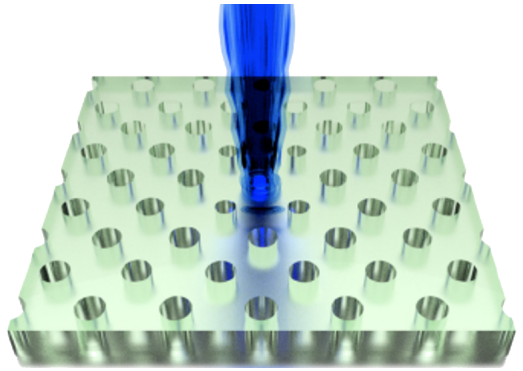
Figures reprinted/adapted from Anderson, P. D.; Fischer, A. J.; Koleske, D. D.; Gunning, B. P.; Subramania, G., *Optical Materials Express* **2018, *8*** pp3543-3550.; Copyright 2018 OSA.

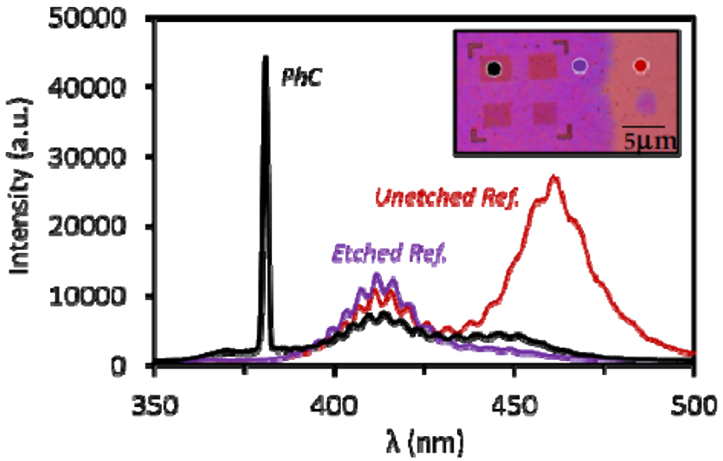
Photoelectrochemical Etching (PEC)

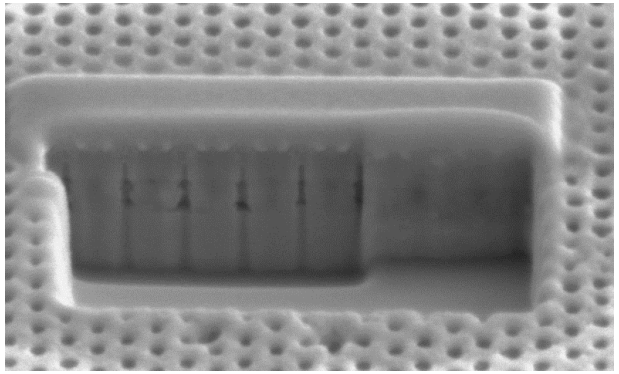
- Electrochemical etch is performed under laser illumination
- Laser wavelength is selected such that it is shorter than the energy gap of 16% InGaN but longer than that of 10% InGaN
- Selective etching of 16% InGaN MQW
- Creates low index cladding layer

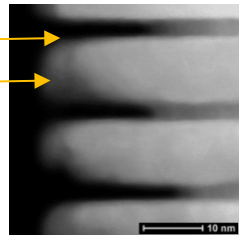












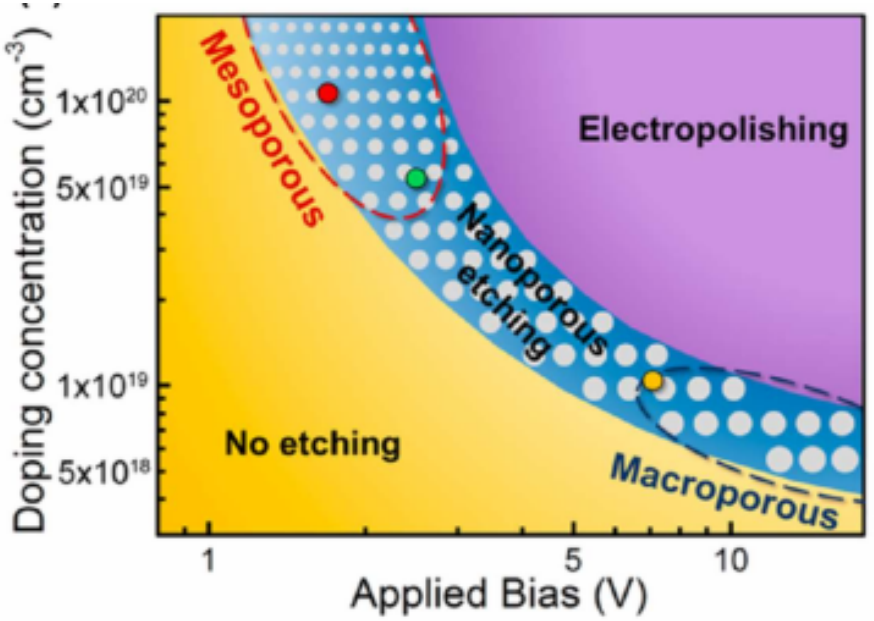
- Removal of InGaN QWs by PEC reduces cladding layer index but procedure is challenging
- Hard to scale for thicker cladding

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

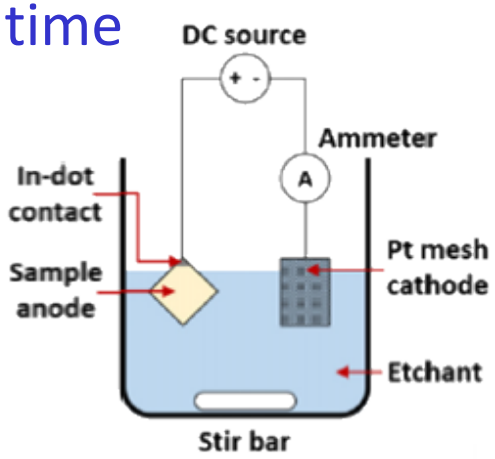
Nanoporous III-N Low Index Layer

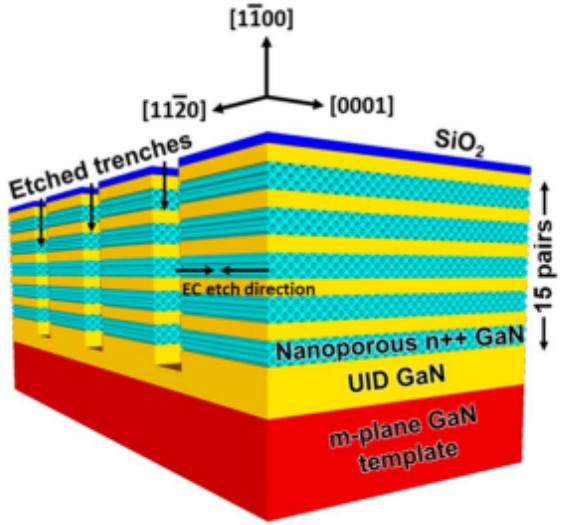
Electrochemical (EC) etching of doped III-N layer in chemical bath

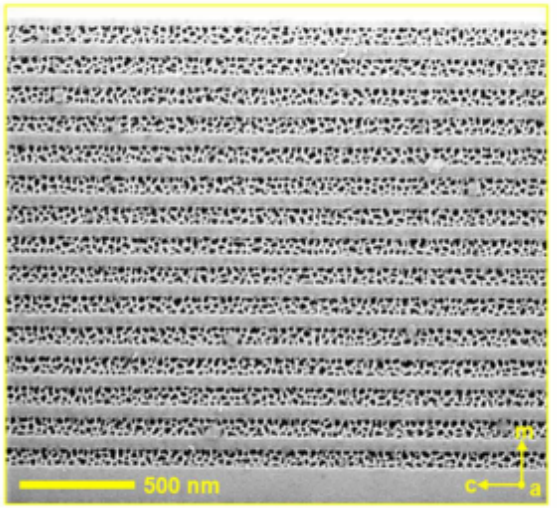
- Etching conditions - applied voltage, doping concentration, etching time



Feezell Group (UNM)





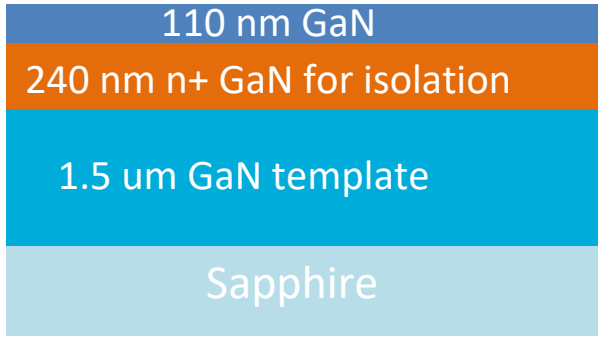


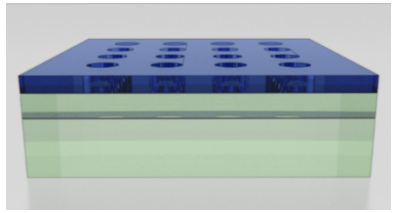
Approach is flexible and scalable

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

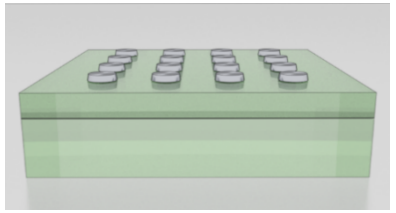
Figures adapted from Mishkat-Ul-Masabih, S et. al. *Applied Physics Letters* **2018,** *112* (4), 041109

III-N Nanowire Array Resonators

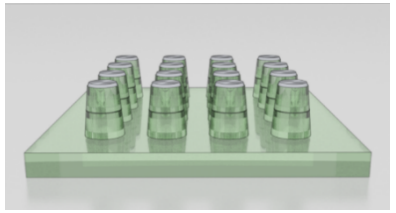




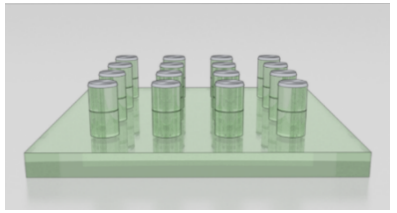
EBL pattern in PMMA



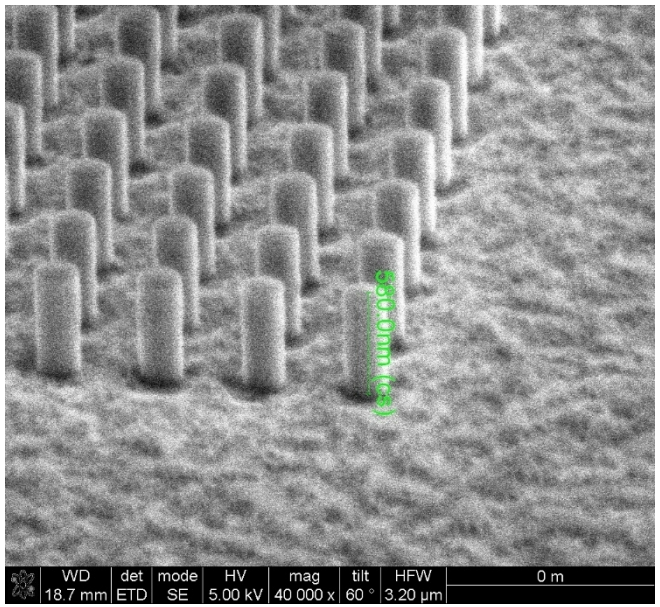
Ni evaporation and lift-off

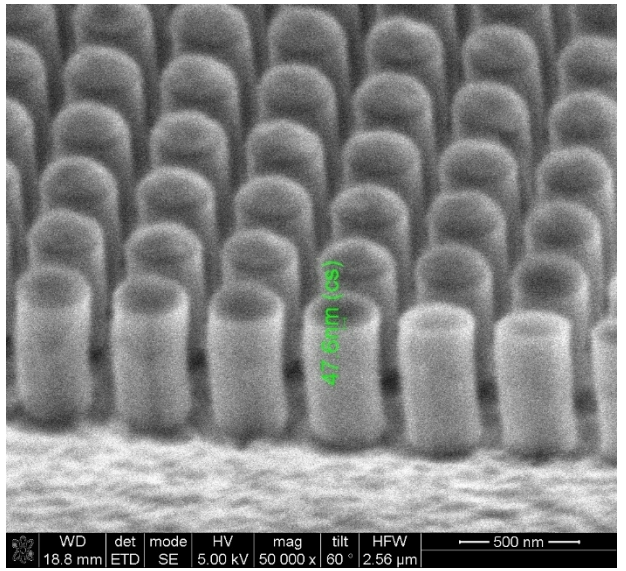


Cl_2 based dry etch



KOH based wet etch





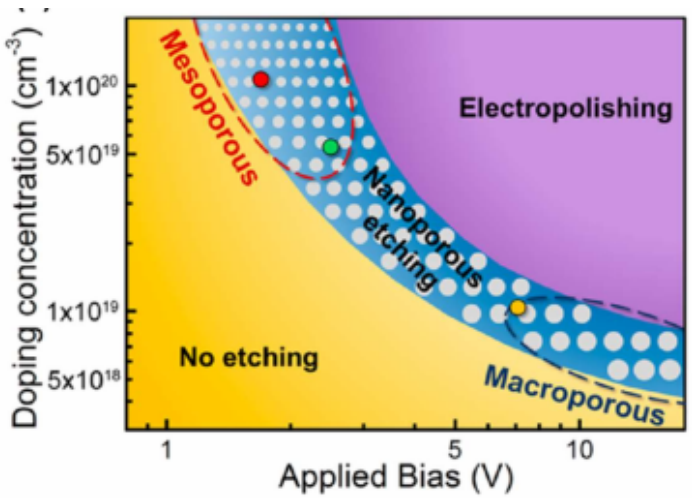
Demonstration of cylindrical GaN nanowire array with smooth side walls

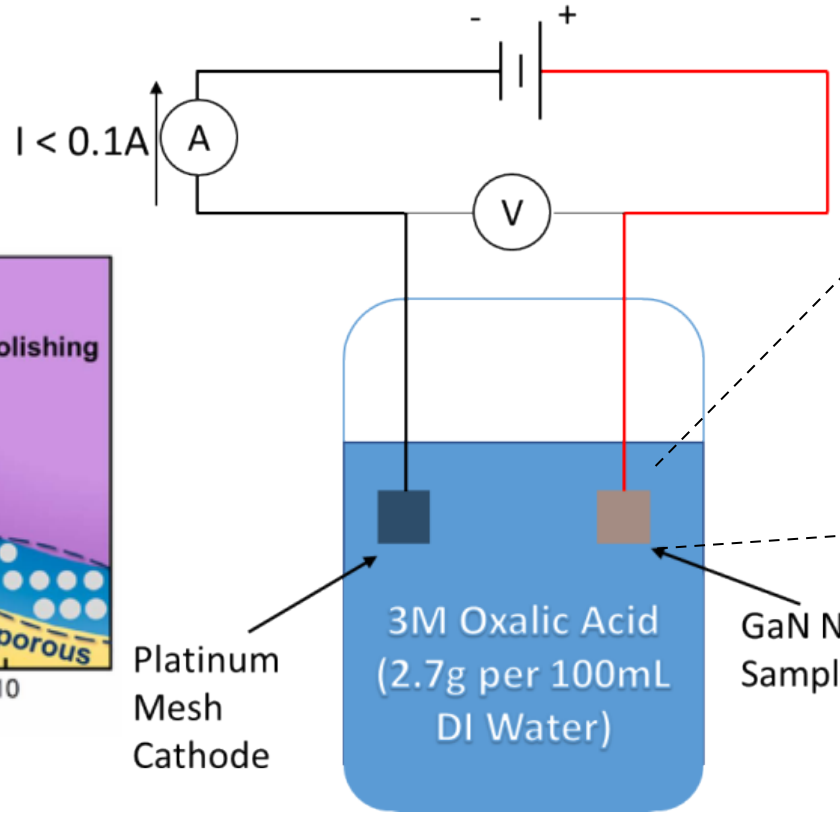
Electrochemical Etching Process

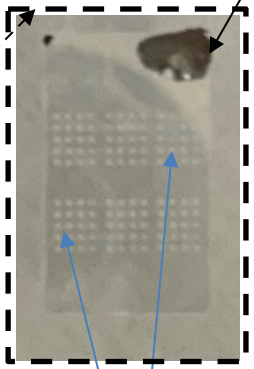
In collaboration with Prof. Daniel Feezell's group (UNM) [Grad students Zach Meinelt and Elizabeth Dejong]

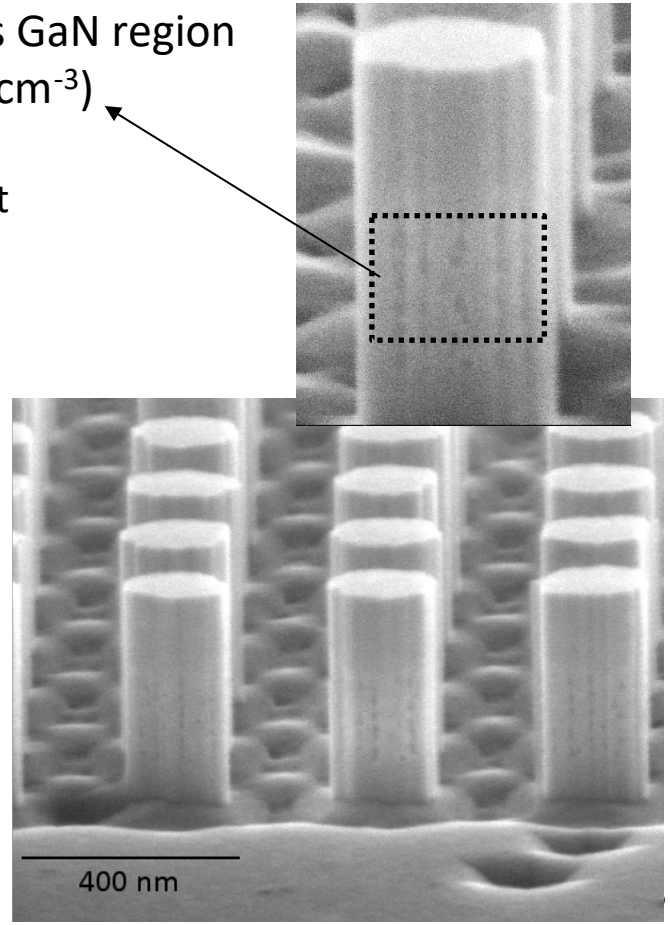
Electrochemical etching of doped GaN layer in acidic solution

- Results in nanoporous region with lower effective refractive index

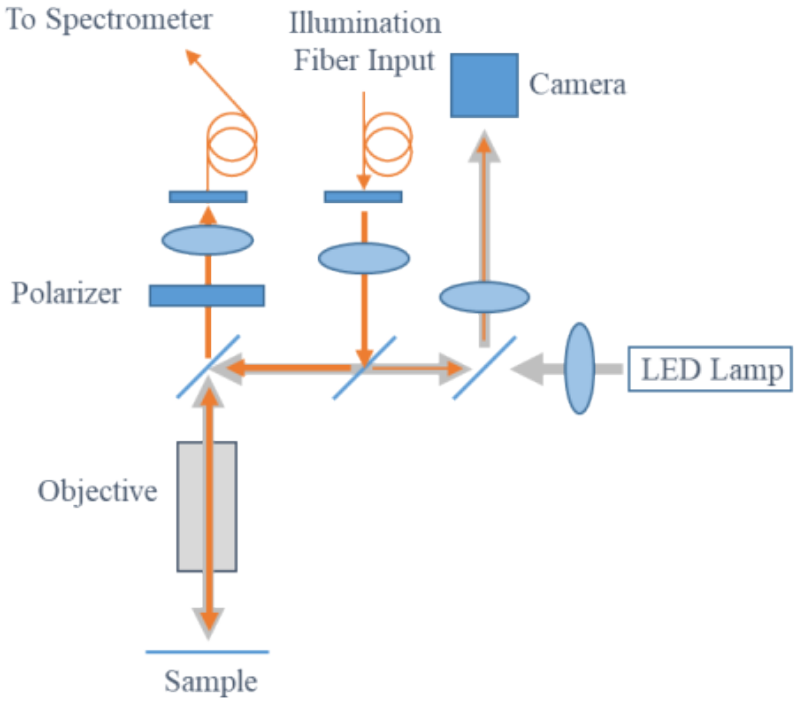




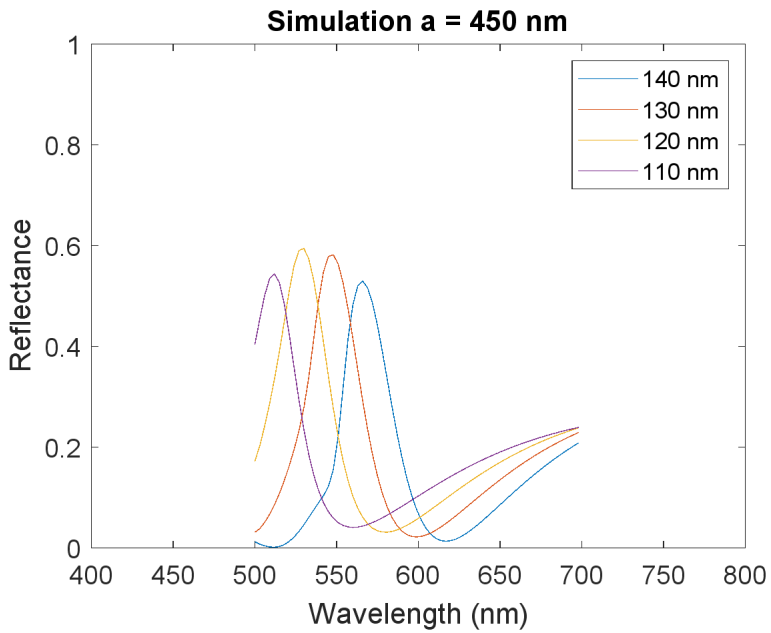




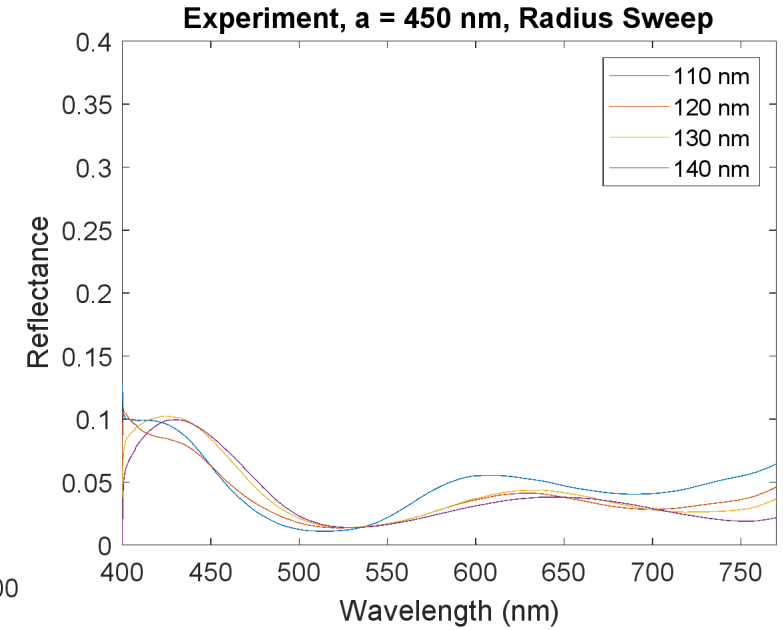
Optical Reflectance



EM simulation



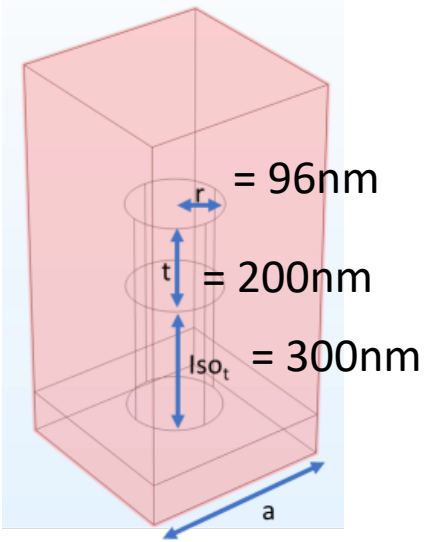
Optical measurement



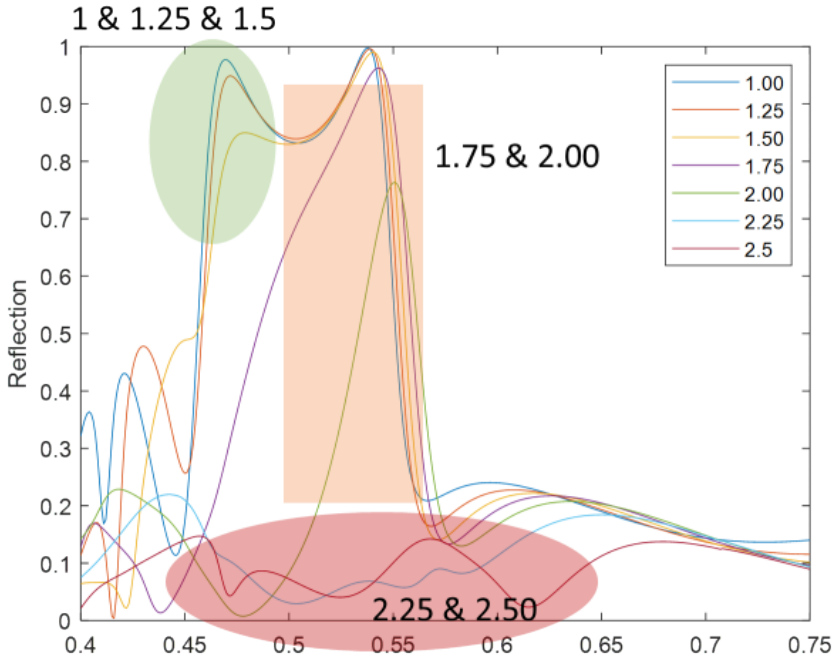
- Weak reflectivity response made porosity characterization difficult

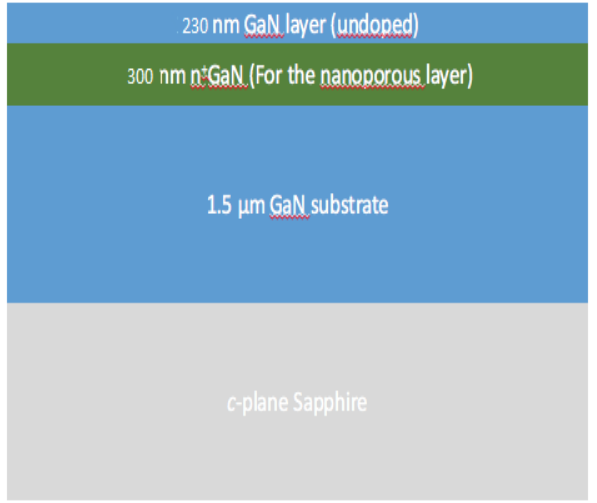
Design of Modified Metasurface

- Modified metasurface design to characterize cladding effective index
  - Provides unique optical reflectance signatures corresponding to cladding layer effective index



a = 400 → 450nm



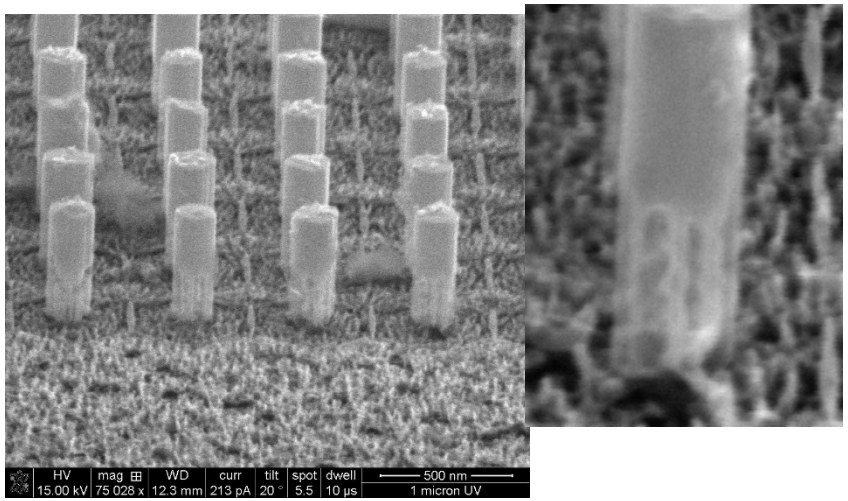


Utilized both approaches to create low-index cladding : 1) selective undercut 2)EC etched nanoporosity

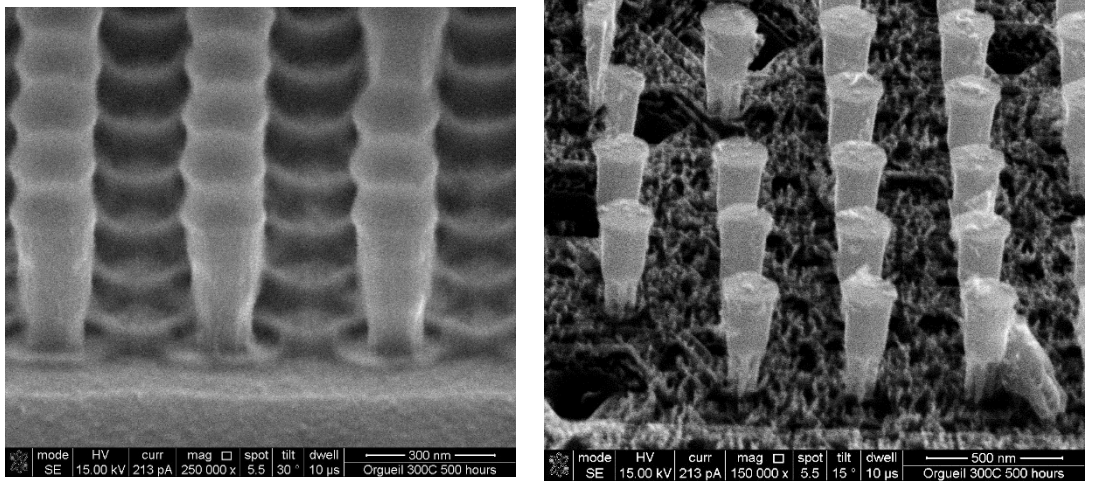
Porosity Characterization

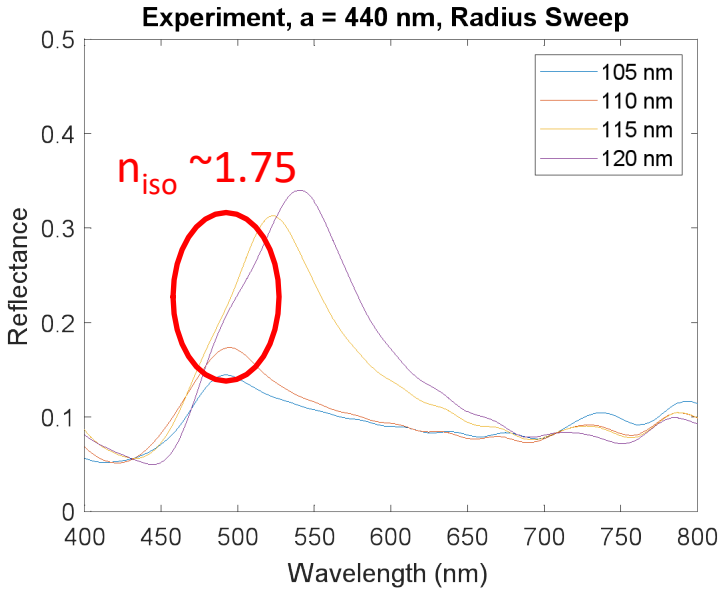
(24 V, 12 min)

EC etch



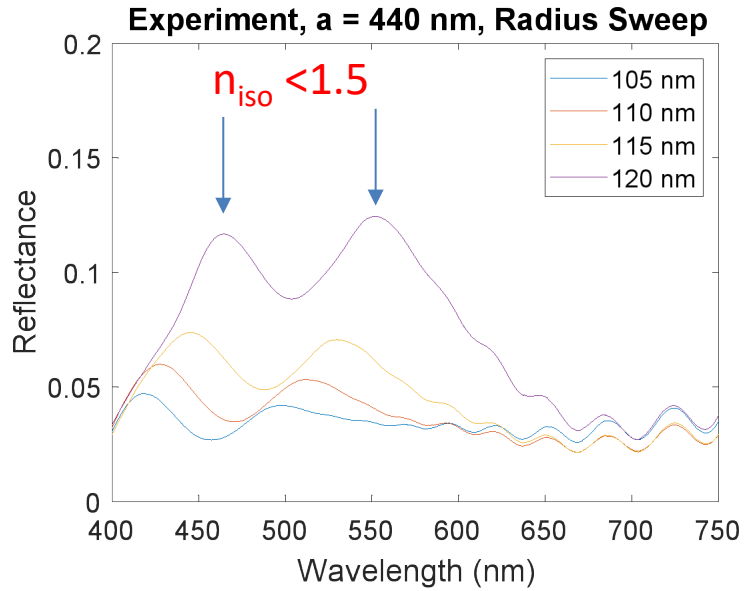
Blanket wet etch (KOH) + EC etch





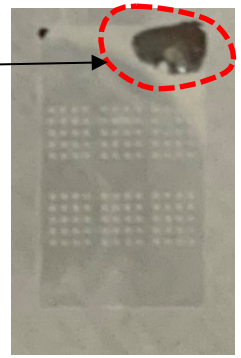
Using our characterization design, the nanowire resonators show a clear reflectivity response enabling porosity/effective index characterization.

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

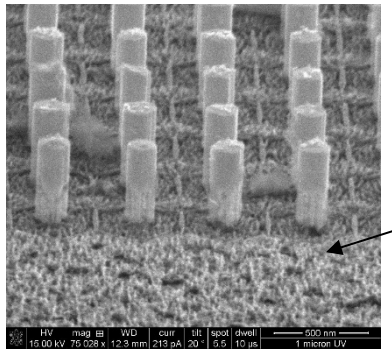


Improved EC etching approach

- Controlled etch depth
- Indium contact annealed at 150°C
- EC etch 24V, 12min



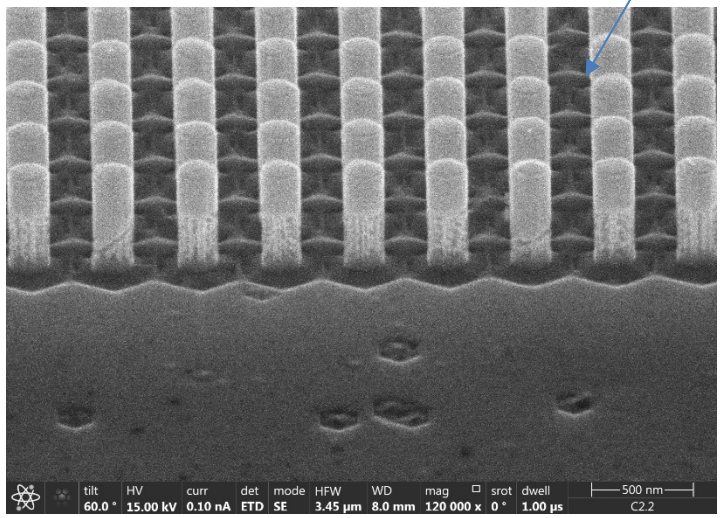
Previous

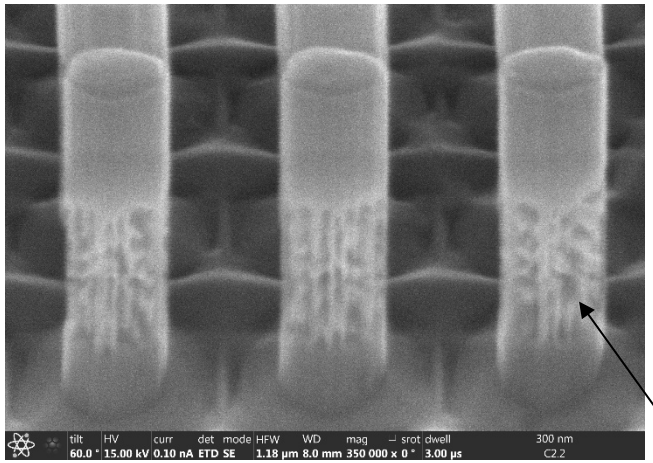


‘grassy’ surface

cleaner surface

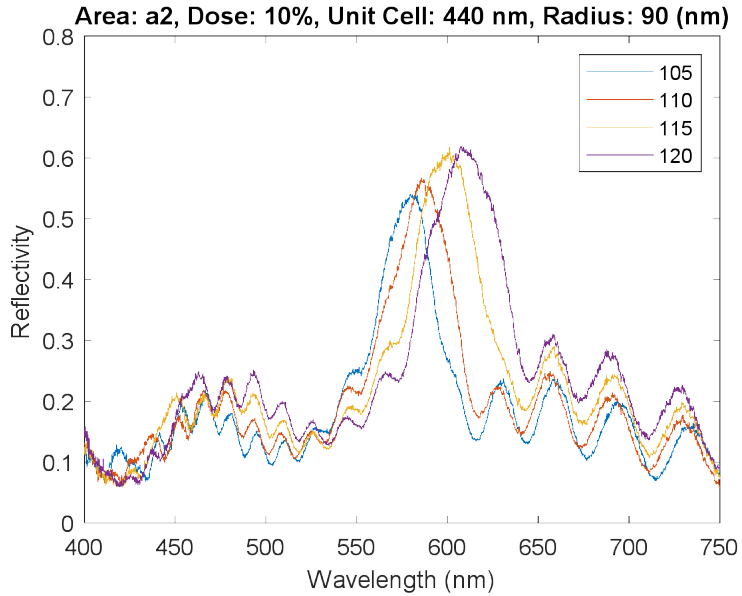
Current





Porous high

Considerably improved reflectivity response from resonators



Summary

- Fabrication of III-nitride metasurfaces
- Approach to low refractive index substrate isolations: PEC and EC etching
- Optical measurement
  - Different cladding index range shows qualitatively different spectral response