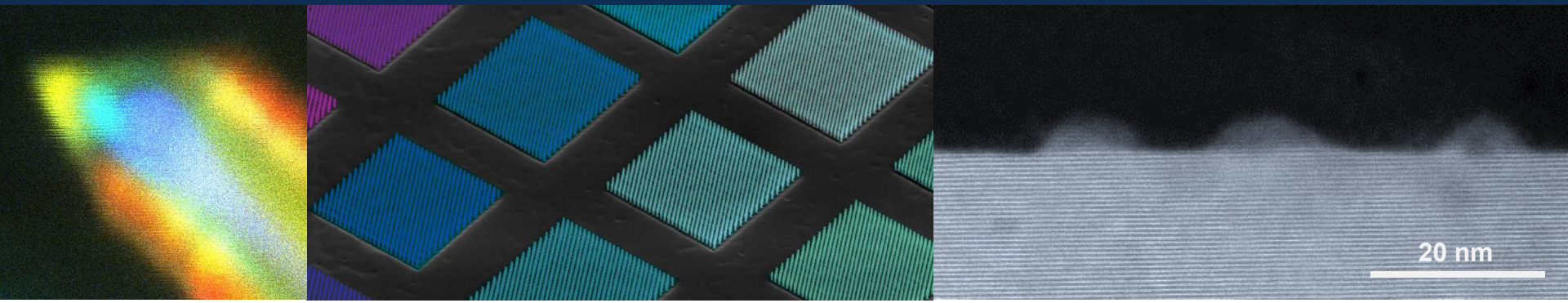
SAND2015-7803PE

Exceptional service in the national interest

Sandia National Laboratories



Nanostructures for Solid-State Lighting

George T. Wang

Sandia National Laboratories

2015 U.S. DOE SSL Roundtable, Sep. 9, 2015, Washington, D.C.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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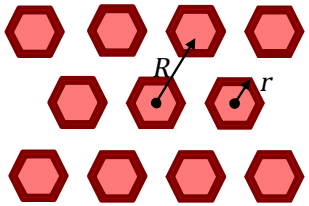
III-N Nanostructures for low-cost, reduced droop LEDs

Sandia National Laboratories

Vertical device integration

benefit: higher effective device area (cost/droop)

Nonpolar sidewall nanowires

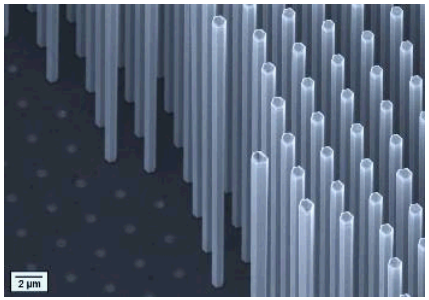


AR = aspect ratio
FF = fill factor

$$\frac{A_{sidewall}}{A_{substrate}} = \frac{6rh}{2.6R^2} \cong \mathbf{4.6}\boldsymbol{AR \cdot FF}$$

*ex: AR=3, FF=0.5 → **6.9× increase!***

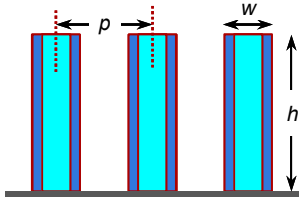
Microrod LEDs (Osram Opto)



Microwire LED IQE~65%

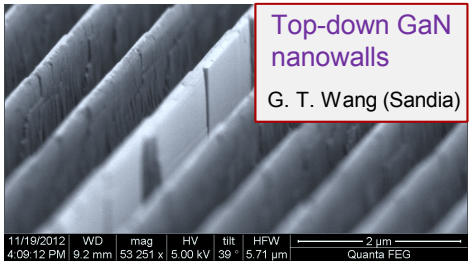
Cpd Semiconductor Mag: *What's The Best Business Model For Nanowire LEDs? (Dec. 14)*

Nonpolar sidewall nanowalls

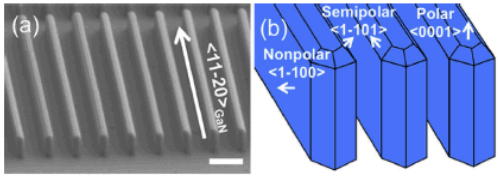


$$\frac{A_{sidewall}}{A_{substrate}} = \frac{2h}{w} \cdot \boldsymbol{F} = \mathbf{2}\boldsymbol{AR \cdot FF} = \frac{\mathbf{2}\boldsymbol{h}}{\boldsymbol{p}}$$

*ex: p=0.5 µm, h=3 µm → **12× increase!***



InGaN/GaN MQWs on m-plane nanosheets



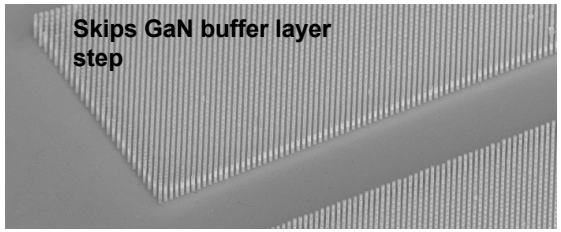
Dapkus (USC), *APL* **100** 033119 (2012)

Complex 3D growth and injection

Use of alternative substrates

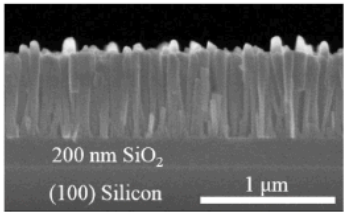
benefit: lower cost, new form factors

Core-shell NW LEDs grown on 8" Si



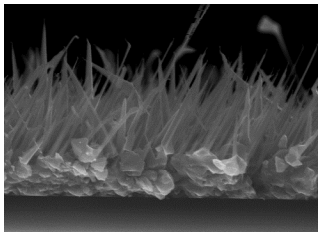
Aledia, Inc.

Nanowire LEDs grown on SiO_2



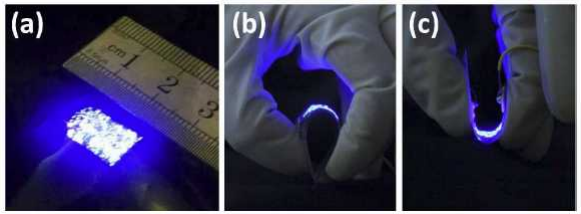
Bhattacharya (Michigan) *Opt. Exp.* **23** A650 (2015)

GaN NWs on tungsten foil



G. T. Wang (Sandia)

Flexible core-shell NW LEDs by MOCVD



CNRS (Grenoble), *NL, just accepted 8/31/15*

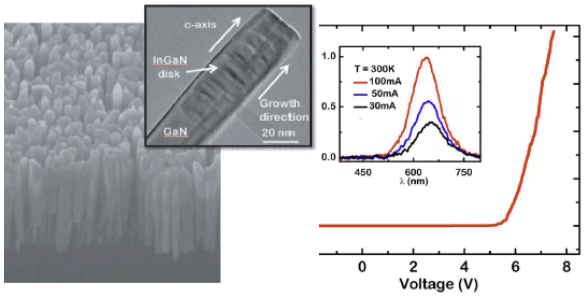
III-N Nanostructures for the Green-Yellow-Red Gap

Sandia National Laboratories

benefit: strain accommodation allows heterostructures with high In content (e.g. green-yellow-red gap)

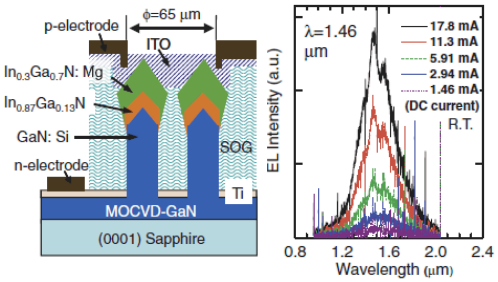
Axial *c*-plane InGaN disc/dot-in-a-wire grown by MBE: long wavelength emission demonstrated

Red emitting InGaN disks-in-wire ~52% IQE



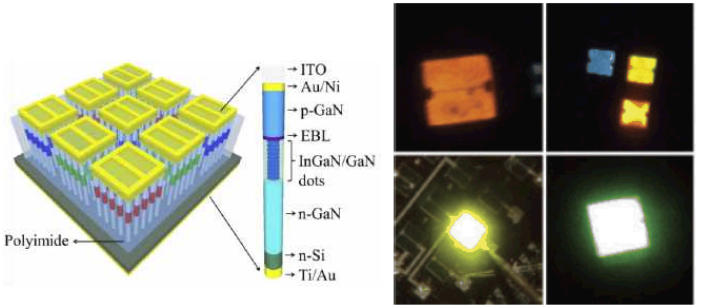
Bhattacharya (U. Michigan) *APL* **102** 071101 (2013)

Near IR InGaN LEDs at 1.46 μm



Kishino (Sophia U.), *APE* **5** 031001 (2012)

Phosphor-free RGB nanowire arrays on Si



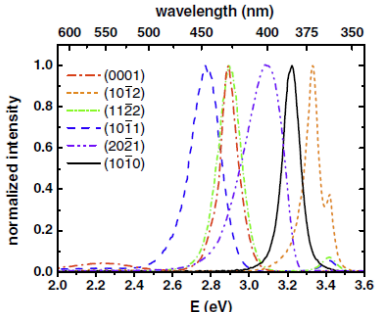
Z. Mi (McGill U.), *Opt. Exp.* **22** A1768 (2014)

Can axial heterostructures be replicated with MOCVD?

Uniform injection of NW arrays an issue

{10-11} Semipolar nanostructures: potentially higher In incorporation

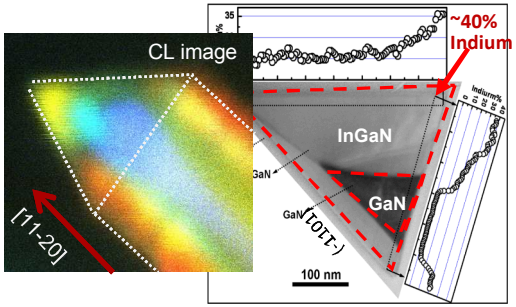
InGaN MQW emission by facet orientation



$(10\bar{1}1) < (11\bar{2}2) = (0001) < (20\bar{2}1) < (10\bar{1}0) = (10\bar{1}2).$

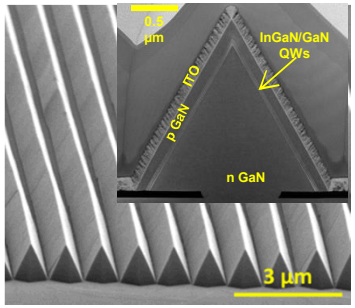
Wernicke (TU Berlin), *SST* **27** 024014 (2012)

High In incorporation on (10-11) NW sidewalls



G. T. Wang (Sandia), *APL* **97** 181107 (2010)

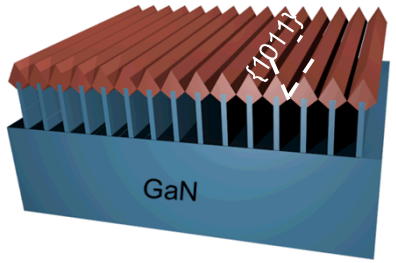
(10-11) semipolar nanowall LEDs



Feezell (U. New Mexico)

See also work by Wunderer (U. Ulm)

InGaN pseudo-templates based on semipolar nanostripes?



G. T. Wang (Sandia)

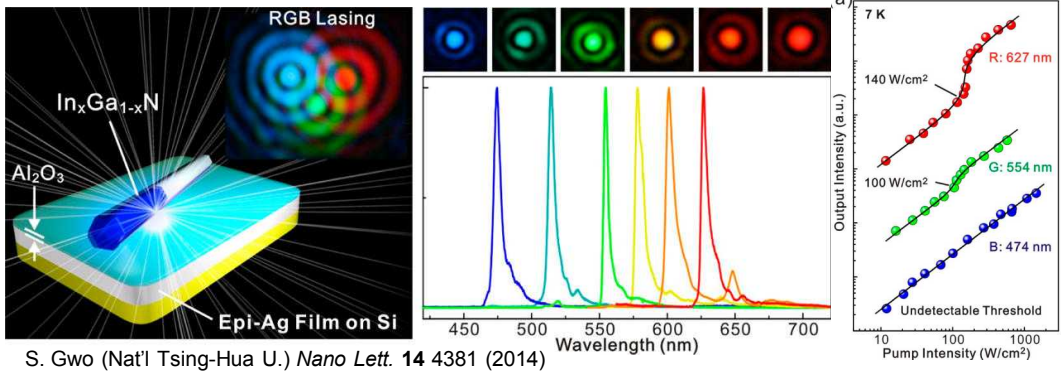
Corner effects (nonuniform In incorporation), material quality?

III-N Nanowire and Quantum Dot Lasers

Sandia National Laboratories

Potential benefits: long wavelengths, low thresholds, higher efficiencies, wavelength tuning, nanophotonics

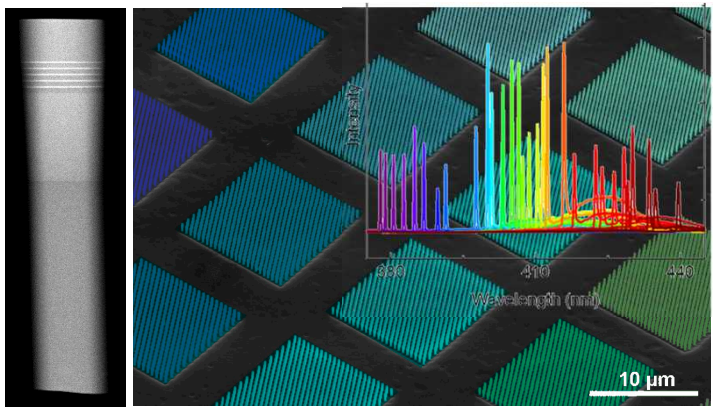
Ultralow threshold full-color plasmonic lasers (Gwo)



S. Gwo (Nat'l Tsing-Hua U.) *Nano Lett.* **14** 4381 (2014)

Ultralow continuous wave threshold across visible spectrum (single NWs on Ag)

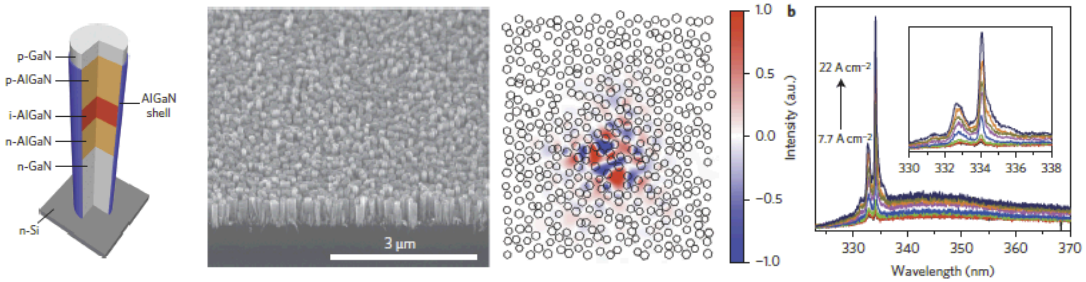
Top-down nanowire photonic crystal laser pixels



J. B. Wright et al. (Sandia) *Sci. Rep.* 3, Art. #: 2982 (2013)

60 nm λ tuning demonstrated purely by PC geometry

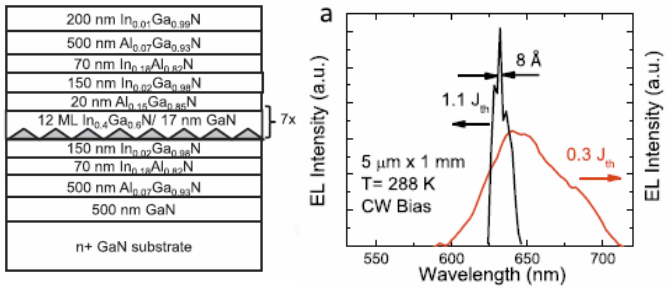
Ultralow threshold electrically injected AlGaN nanowire array UV random laser on Si by MBE



Z. Mi (McGill), *NNANO.2014.308* (2015)

Electrically injected lasing at 263 nm @ 0.6 kA/cm² threshold, deepest UV reported to date

Red Edge-Emitting QD Lasers by MBE



Bhattacharya (U. Michigan) *IEEE J. Quant. Electr.* **49** 923 (2013)

~36% IQE at 630 nm, 2.5 kA/cm² threshold

Aboslute EQEs and Output Powers?

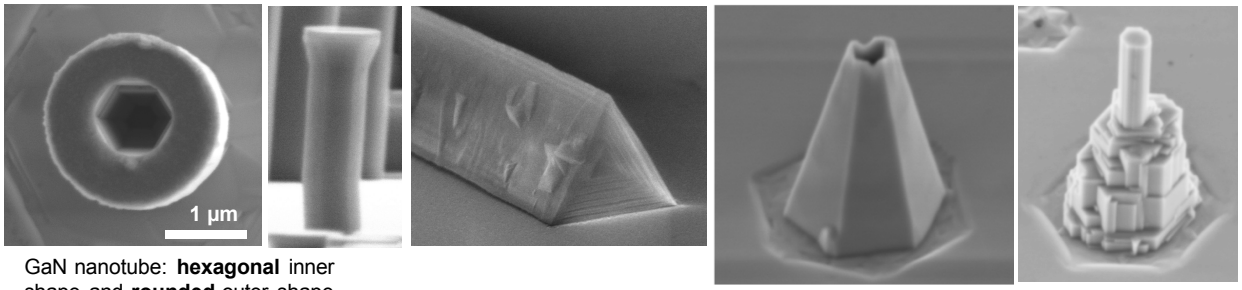
Electrical Injection for single NWs?

MOCVD Compatible Processes?

Tailored Quantum-Scale and 3D Nanostructures

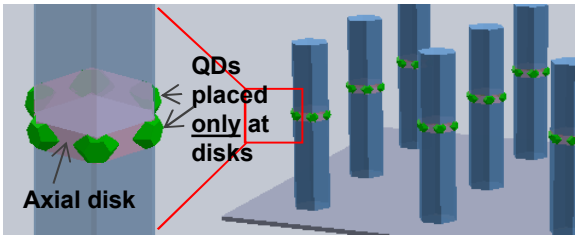
Sandia National Laboratories

Can hybrid approaches that advance and integrate bottom-up and top-down approaches be exploited to realize new classes of architecturally tailored 3D semiconductor nano and meso structures with novel and enhanced optoelectronic properties & functionalities?

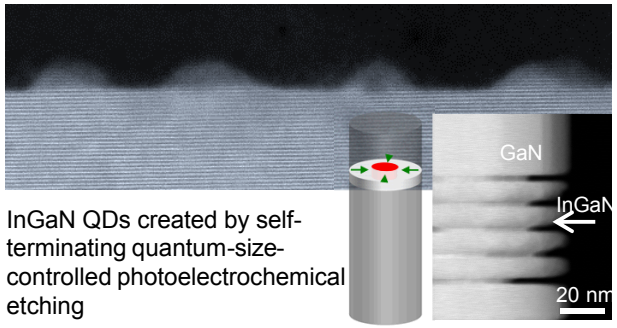


GaN nanotube: **hexagonal** inner shape and **rounded** outer shape

Understanding 3D nanoscale shape evolution via bottom-up growth and top-down etch processes



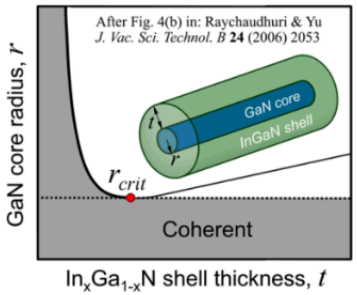
Hierarchical approaches **to create 3D hierachical mesostructures** with deterministic placement of elements



InGaN QDs created by self-terminating quantum-size-controlled photoelectrochemical etching

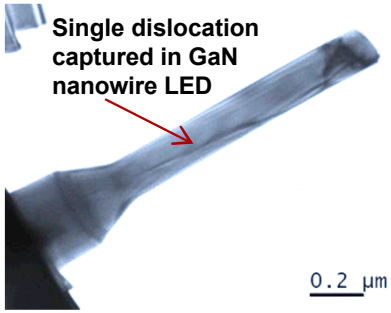
Tsao et al. (Sandia) *Nano Lett.* **14** 5616 (2014)

New paradigm of "quantum nanofabrication" – using *quantum size effects* for precise size control of sub 10 nm quantum structures



Radial **hybrid** nanowire architecture

Compliant synthesis of hybrid integrated nanostructures across materials systems



Using nanostructures to probe property-structure relationship

Sandia National Laboratories

Backup Slides

III-N Nanostructures for the Green-Yellow-Red Gap

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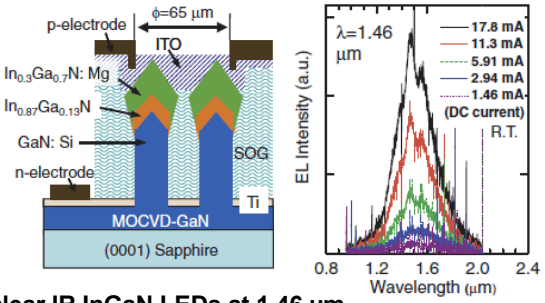
Benefit: strain accommodation allows heterostructures with high In content (e.g. green-yellow-red gap)

Axial *c*-plane InGaN disc/dot-in-a-wire grown by MBE

Kishino (Sophia U.), *Appl. Phys. Exp.* **5** 031001 (2012)

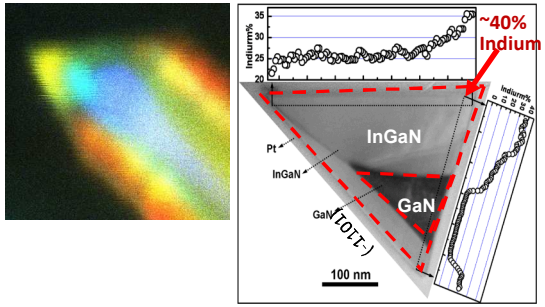


Near IR InGaN LEDs at 1.46 μm

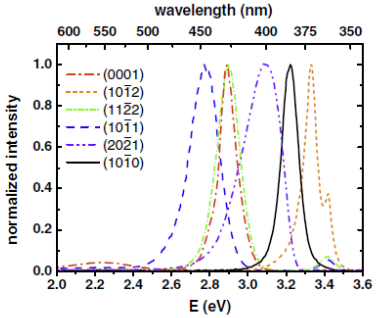
Red emitting 650 nm InGaN disk-in-a-wire with ~52% IQE

S. Bhattacharya (Michigan) *APL* **102** 071101 (2013)

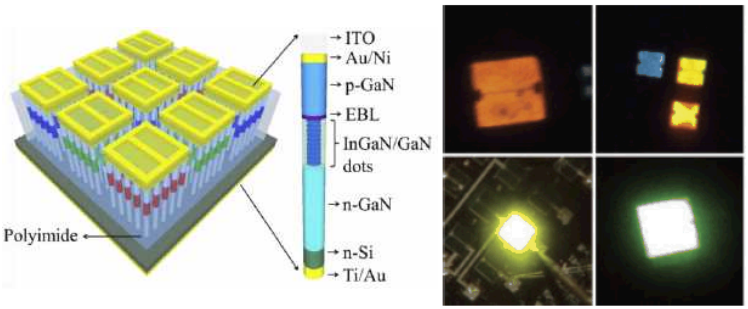
Semipolar nanostructures



G. T. Wang (Sandia), *APL* **97** 181107 (2010)

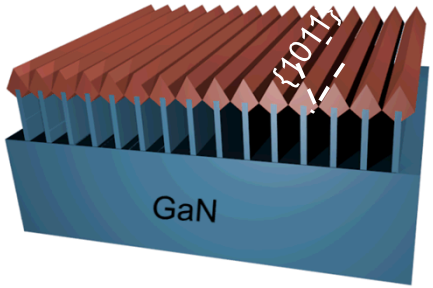


Wernicke (TU Berlin), *SST* **27** 024014 (2012)

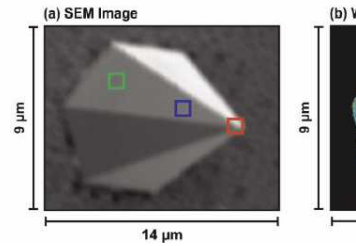


Phosphor-free RGB nanowire arrays integrated on Si

Z. Mi (McGill U.), *Opt. Exp.* **22** A1768 (2014)



InGaN nanowire pseudo-templates?



Wunderer (U. Ulm), *PSSb* **24**

Can process be replicated with MOCVD?