SAND2016-4475PE

Solid-state lighting and III-nitride semiconductors

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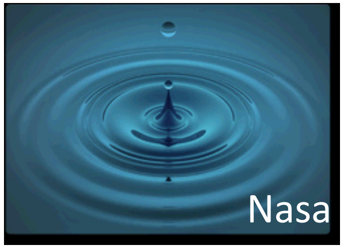
Outline

- Lighting
  - Life, vision, world economics
- III-N LED’s
- Nanowire Lasers
- Lasers for lighting

What Waves in Light?



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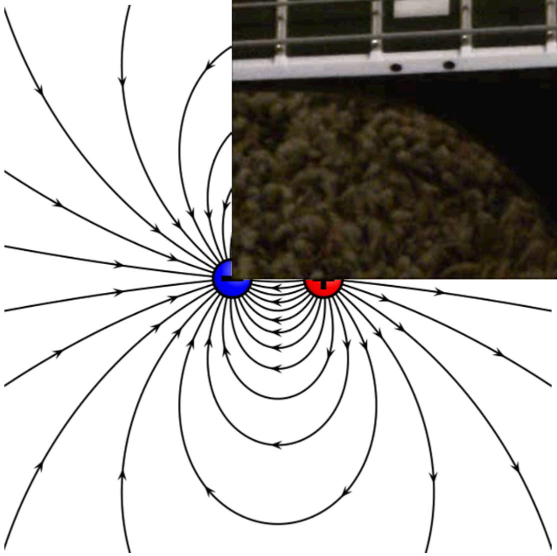
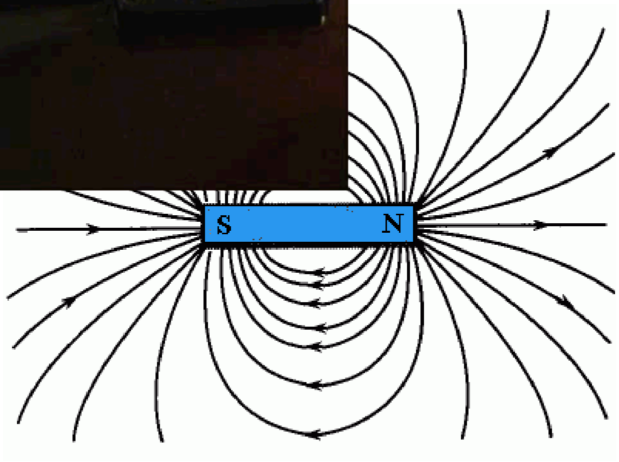
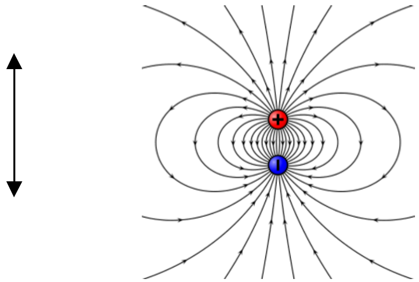


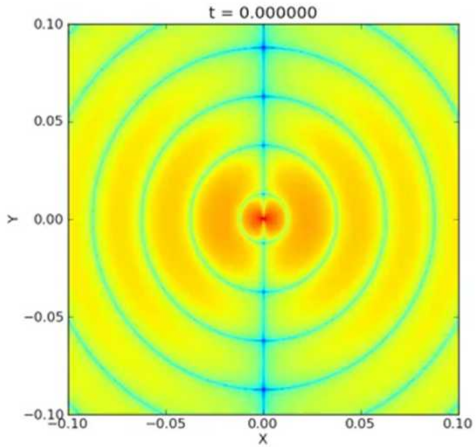
(wikibooks)



(antenna-theory.com)

Changing Fields Can Generate Waves





(http://youtu.be/Lx7LNVtQvTs)

Unified electromagnetics and predicted waves

James Clerk Maxwell

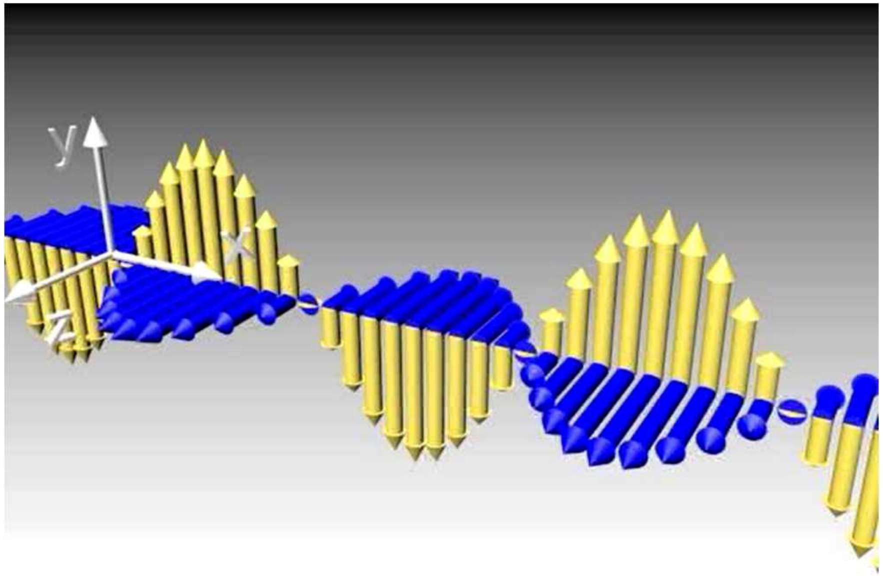
20-30 yrs →

Measured E&M waves (1883)

Heinrich Hertz

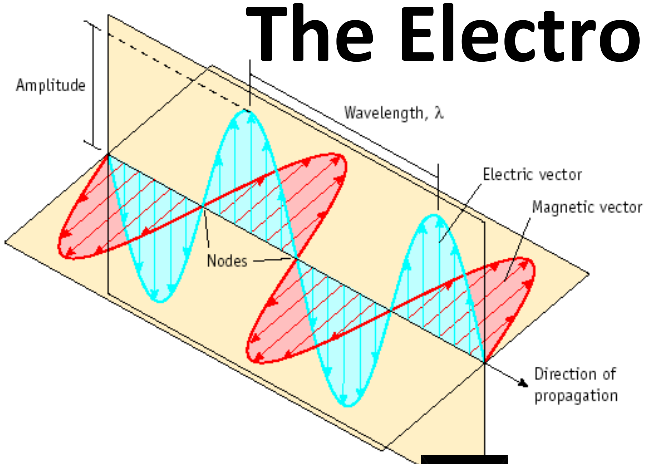
<u>**The Electromagnetic Wave**</u>

- Electric and magnetic fields go together and are perpendicular to the propagation direction
- They carry energy

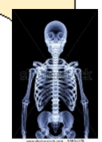


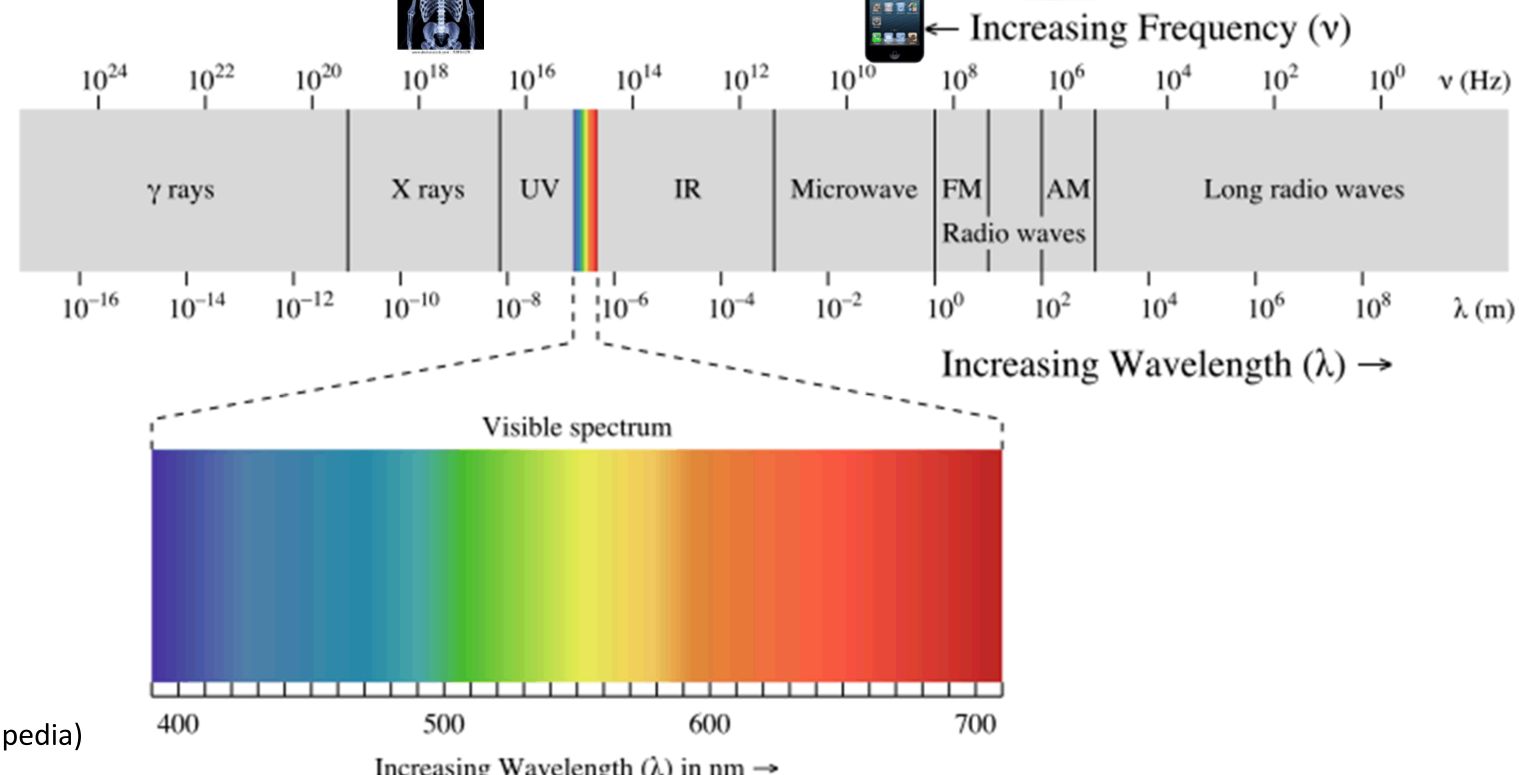
(MIT)

The Electromagnetic Spectrum



Frequency=c/λ

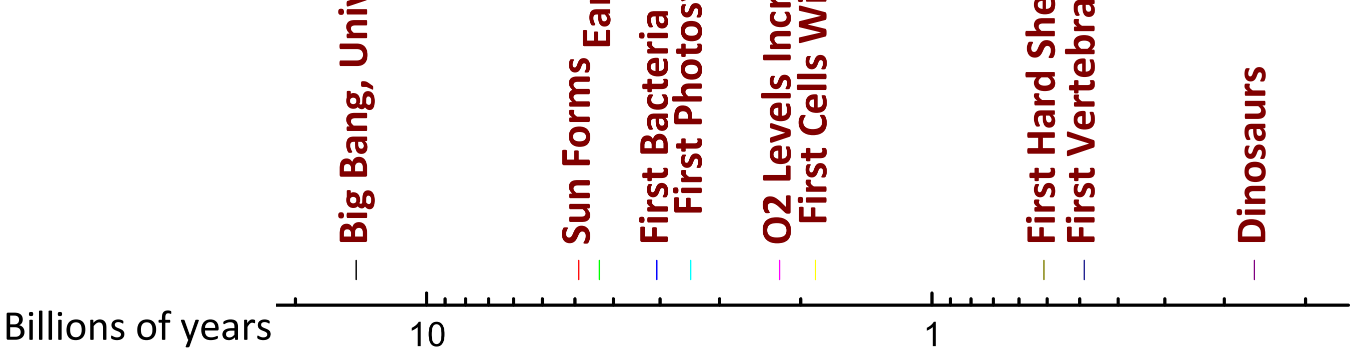


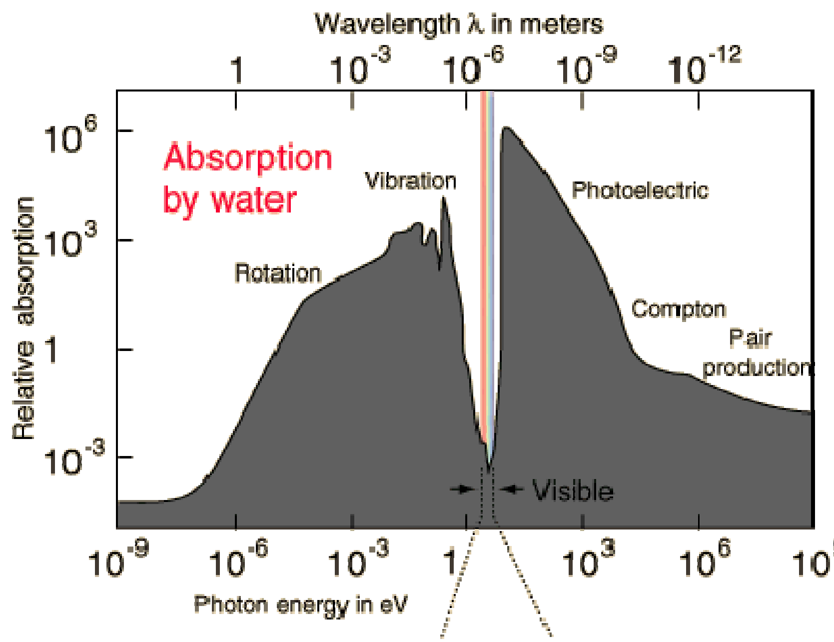


(source: wikipedia)

Light, Life and Vision

In the beginning there was nothing. God said, "Let there be light!" And there was light. There was still nothing, but you could see it a whole lot better. ***Ellen DeGeneres***

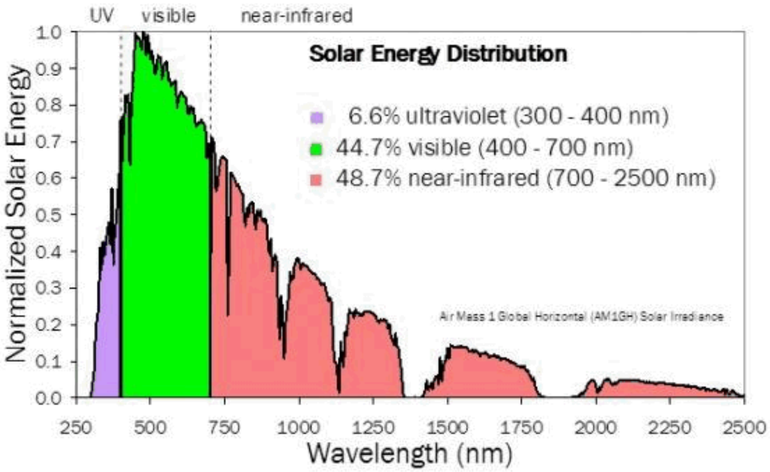




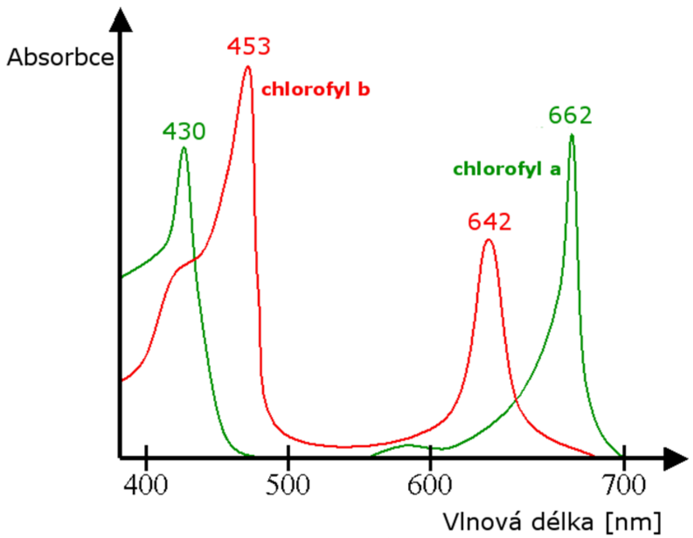
Light, Life and Vision

Why does photosynthesis use visible light?
Why do we see just visible light?

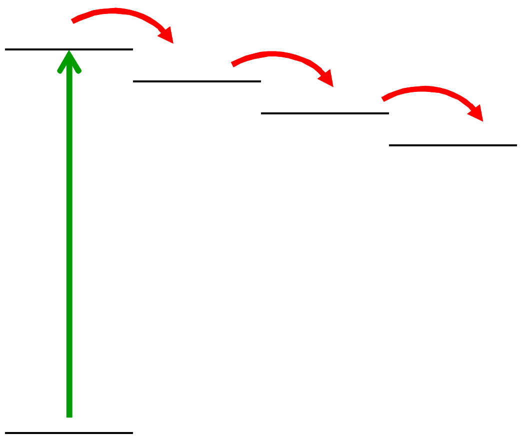
Solar Spectrum

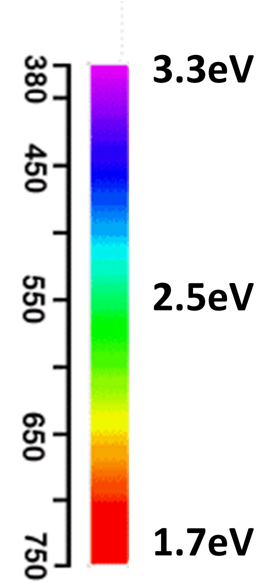


(source: LBL)



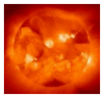
Some molecule absorbs a photon and then energy is transferred and converted





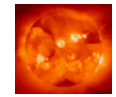
Most organic molecules absorb in the visible. UV photons have too much energy and create free radicals. Infrared photons don't have enough energy to trigger reactions

Light from the Sun and Moon: Trilobites, Birds, Mammals, Primates, Humans

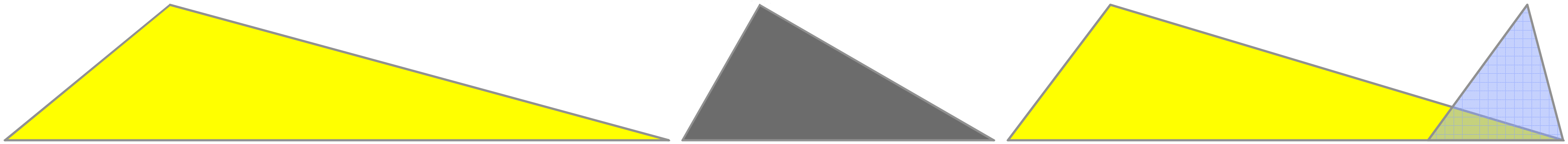


Full-disk view of the X-ray Sun and was produced by the Yohkoh solar observatory in 1991. http://en.wikipedia.org/wiki/File:Yohkohimage.gif

Full moon view from Earth in Belgium, courtesy of Luc Viatour. http://en.wikipedia.org/wiki/File:Full_Moon_Luc_Viatour.jpg



Bridgelux Helieon Solid-State Lamp. http://www.bridgelux.com/products/helieon.html



Asaphus species (Trilobite) picture taken by DanielCD. http://en.wikipedia.org/wiki/File:Asaphus_species_trilobite.jpg

Red Lory (Eos bornea) upper body preening feathers. http://en.wikipedia.org/wiki/File:Red_Lory_%28Eos_bornea%29-6.jpg

Gray wolf, canis lupus, courtesy of Chris Muiden. http://en.wikipedia.org/wiki/File:Canis_lupus_265b.jpg

Olive baboon in Kenya; courtesy of Ryan Harvey; http://en.wikipedia.org/wiki/File:Male_Olive_Baboon_2.jpg

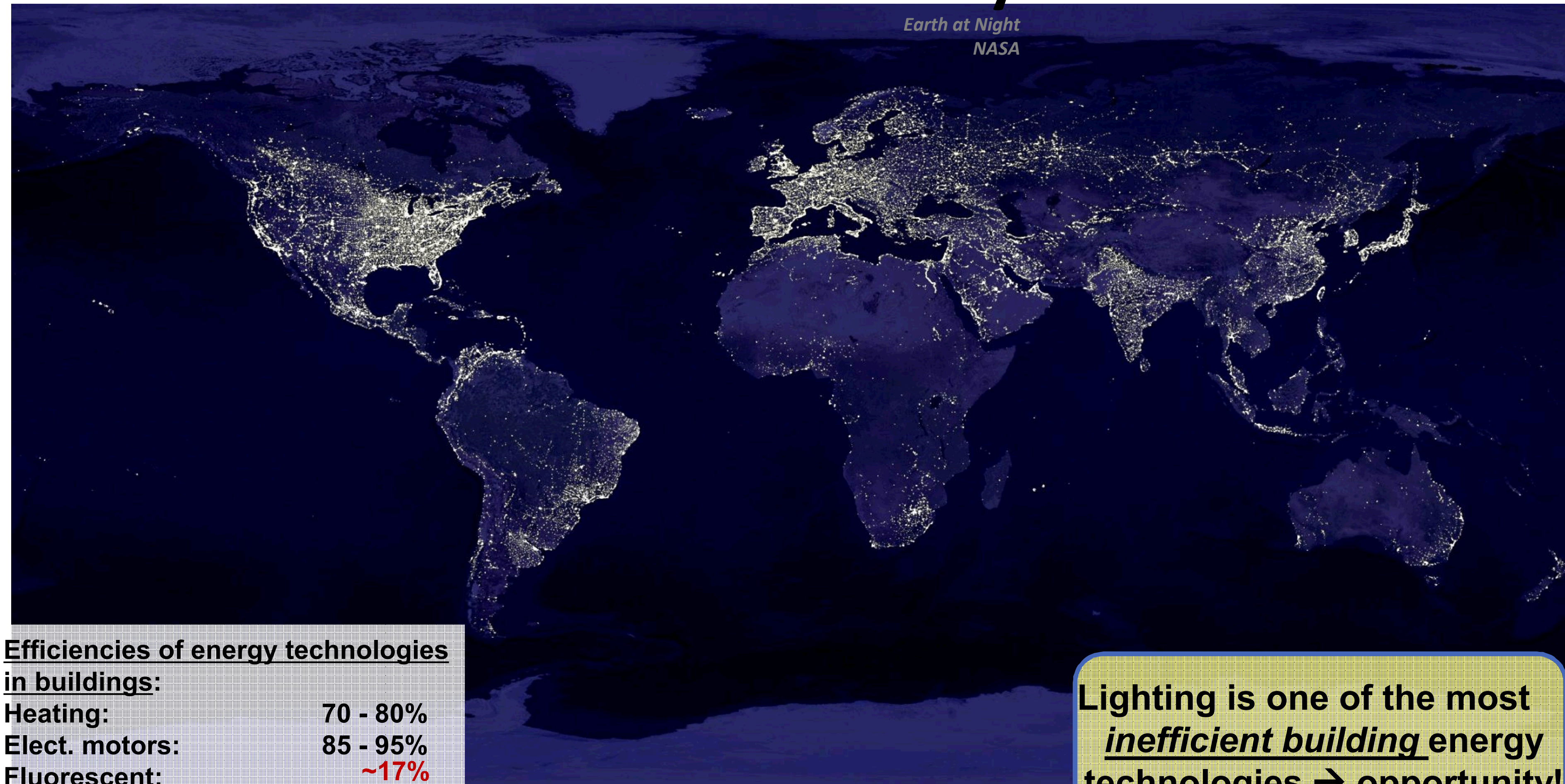
A baby wearing many items of winter clothing: headband, cap, fur-lined coat, shawl and sweater. Courtesy of Andrew Vargas, Clovis, United States. http://en.wikipedia.org/wiki/File:Well-clothed_baby.jpg

(wikipedia)

Mantis Shrimp: 16 different photoreceptor pigments, 12 for color sensitivity, others for color filtering, polarization, etc

Courtesy, Jeff Tsao

Lighting: Large Fraction of Energy Use and Low Efficiency



Efficiencies of energy technologies in buildings:

Heating:	70 - 80%
Elect. motors:	85 - 95%
Fluorescent:	~17%
Incandescent:	~4%

Lighting is one of the most *inefficient building* energy technologies → opportunity!

- **~22% of US electricity is for general illumination (~1/15 world's energy, $330B in 2005)**
- **Achieving 50% efficient lighting would have tremendous global impact**

Holonyak in 1965 speculated that laser light sources were possible (in 10 years or more)

February 1963 Reader's Digest 35¢

a TV broadcast from the air and beaming it by invisible infrared light 275 feet to a receiver, with good reception. The bit of metal alloy they used was not a laser, for it did not comb the tangles out of the light beam, but its performance sparked a tremendous research drive. Last fall several outfits, including General Electric, IBM, RCA and Lincoln, produced metal lasers which emit "coherent" or tuned light. These appear to be destined for a great future in the communications field.

The latest dramatic laser discovery, made by General Electric, may someday make the electric light bulb obsolete. While the radiation from previous lasers was invisible, this one emits *visible* light in the red region of the spectrum. Research is continuing, and GE engineers hope to build lasers which will convert ordinary electric current into white light with a high degree of efficiency.

"We believe there is a strong possibility of developing the laser as a practical light source," says Dr. Nick Holonyak, head of General Electric's Advanced Semiconductor Laboratory. "Much more experimental work must be done, and it might be ten years or more before such a lamp could be ready for wide use. However, within a year we should have them ready for computer indicators and many other electronic devices, where they should be very useful because of the small size, and speed of action."

If these plans work out, the lamp of the future may be a speck of metal the size of a pencil-point which will be practically indestructible, will never burn out, and will convert at least ten times as much current into light as does today's bulb.

Light of Hope—Or Terror?

The present and potential uses of the laser—a new kind of light ray—sound like science fiction. In fact, the invention is one of the most amazing accomplishments of our time

By Harland Manchester

One evening last May, a thin streak of red light shot through space from the roof of M.I.T.'s Lincoln Laboratory at Lexington, Mass., hit the moon (then 250,000 miles away), and bounced back to an instrument which recorded its pioneering round trip. The light came from a new kind of electric torch, called a "laser," which emits a slender pencil of regimented light unlike anything known before. The beam of an ordinary searchlight aimed at the moon would fan out to a circle 25,000 miles wide; its reflection would be too faint to record. The laser beam made a dot only two miles across.

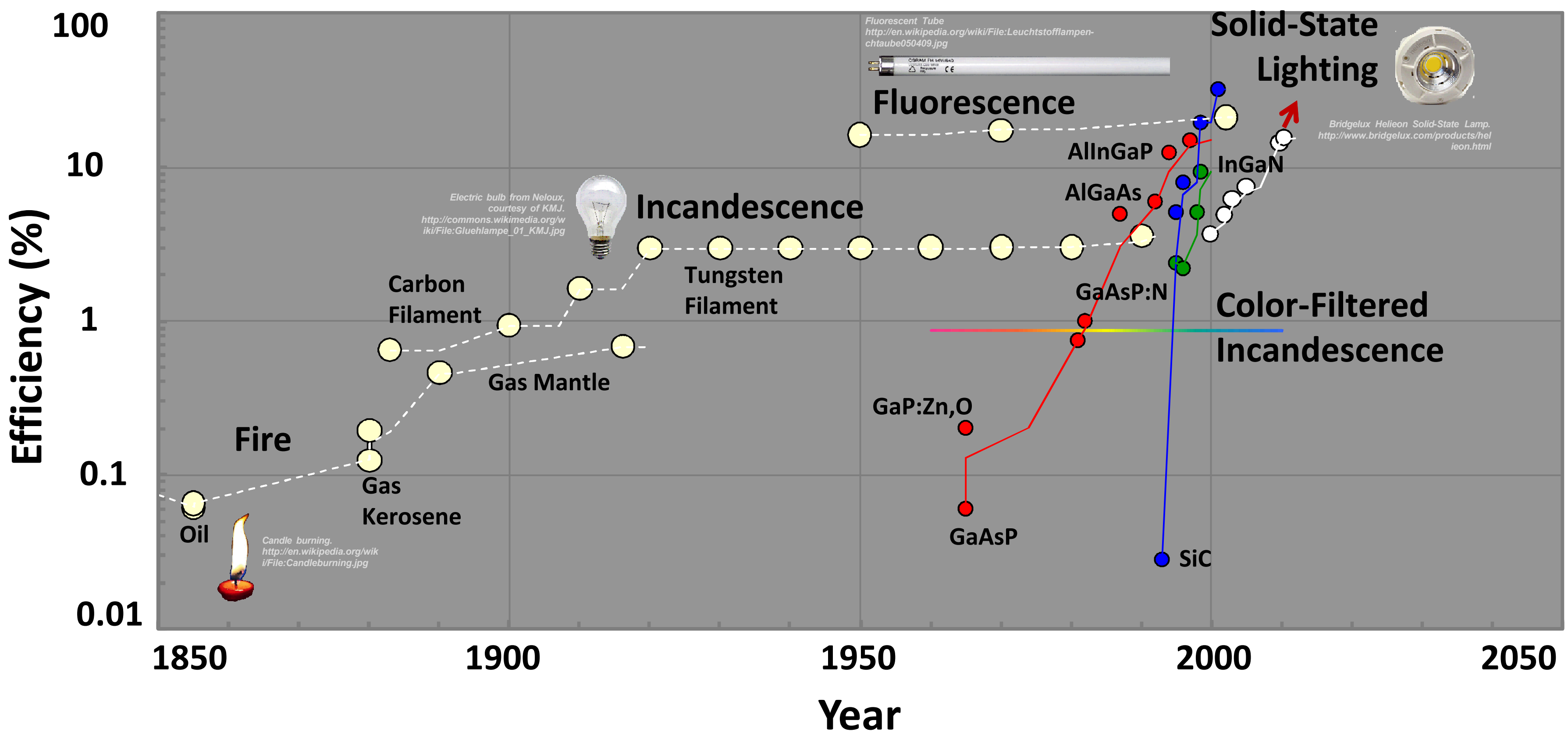
Laser stands for "light amplification by stimulated emission of radiation." Its invention is one of the most exciting events of this century. Since the new light first appeared three years ago, some 400 firms and universities have launched laser research projects, and an estimated 30 million dollars was spent last year in experimentation. Still in its early development stage, the laser prom-

Harland Manchester, a Roving Editor of The Reader's Digest, has specialized in reporting developments in the field of science for many years. His latest book, *Trail Blazers of Technology*, was published last November by Charles Scribner's Sons.

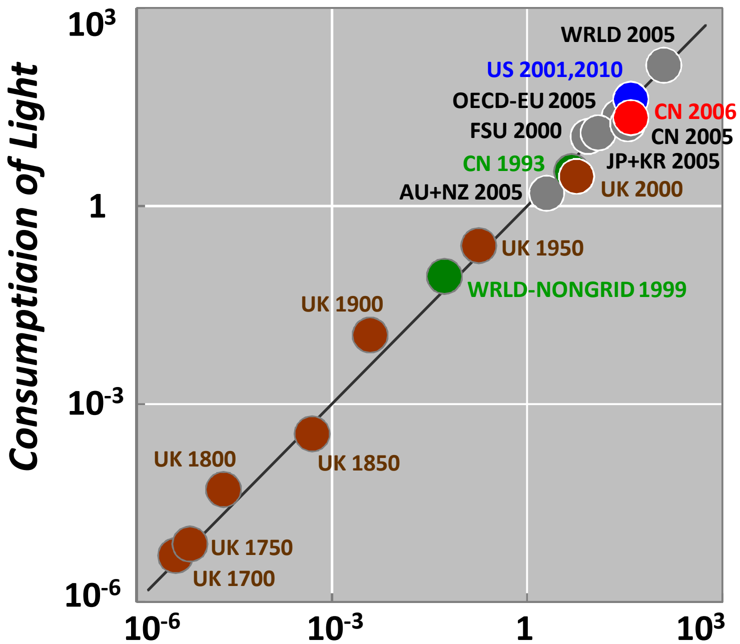
Nick Holonyak

- First visible laser in Oct of 1962.
- Made from GaAsP.
- A working laser diode suggested quantum efficiency was high.
- Further suggests efficient LED.

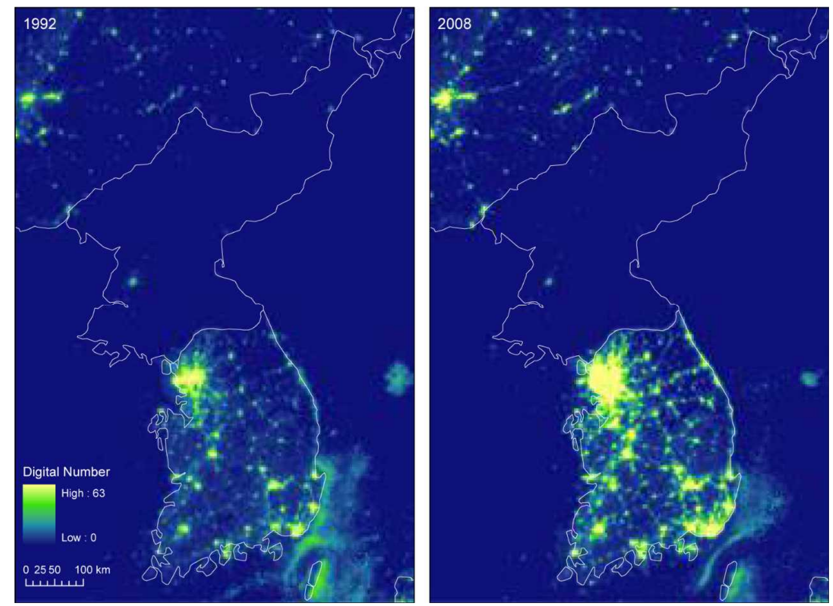
200 Years of Lighting Technology



More light = More productivity



<u>Gross Domestic Product</u>
Cost of Light



1992 **2008**
Korean Peninsula

GDP ↑, Consumption ↑
Cost ↓, Consumption ↑

The more efficiently light is produced the more we consume and the more productive we are

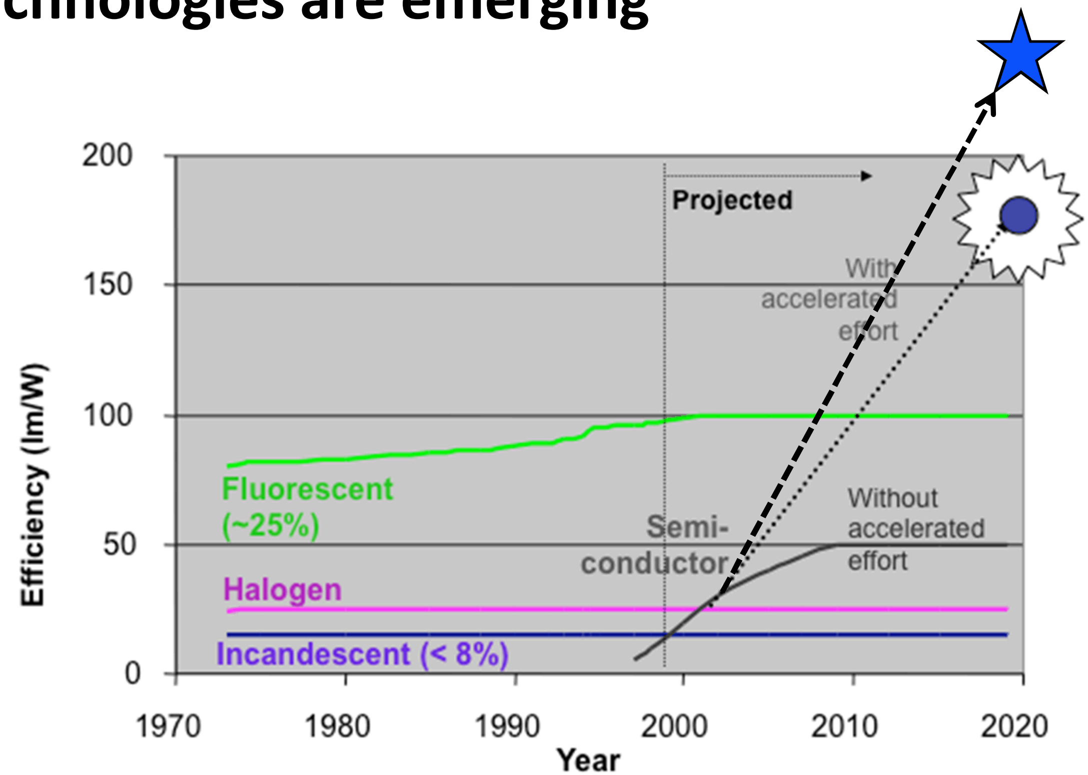
J.Y. Tsao and P. Waide, "The World's Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six Continents," LEUKOS 6, 259-281 (2010).

J.V. Henderson, A. Storeygard, and D.N. Weil, "Measuring Economic Growth from Outer Space," Amer. Economic review 102, 994-1028 (2012).

Blue LED Impacts

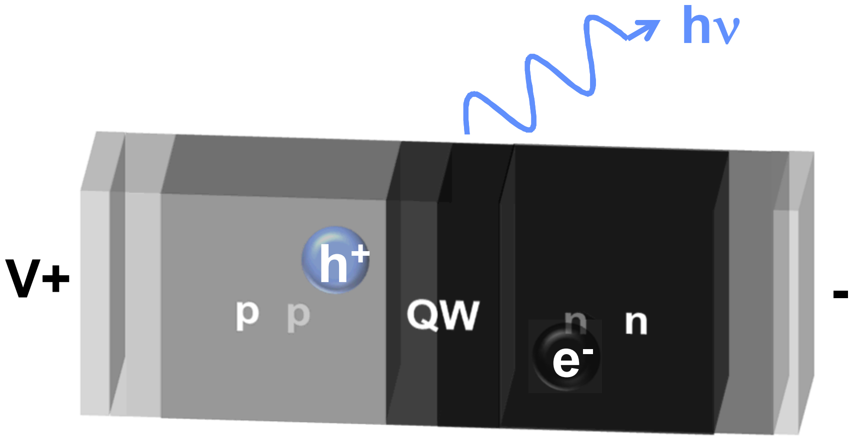
- Global electricity use will drop by ~10%
- Global savings will be ~$140B per year
- Numerous spin-off technologies are emerging

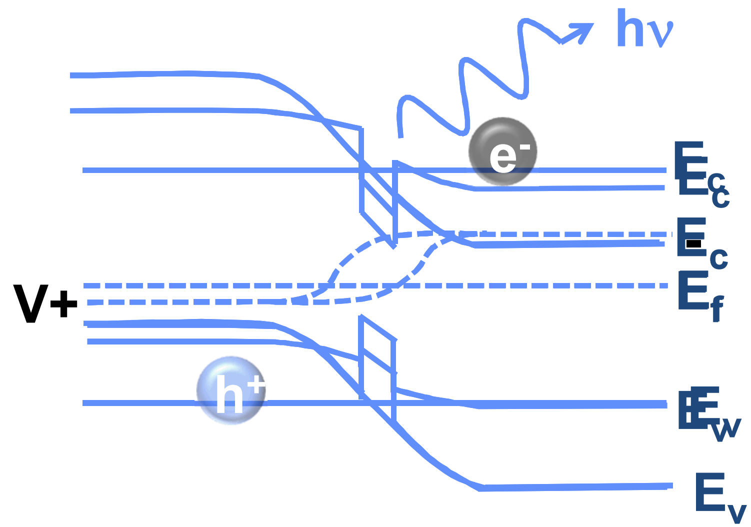
we *underestimated* the impact of solid-state lighting!



Courtesy, Jerry Simmons

P-N junction light-emitters



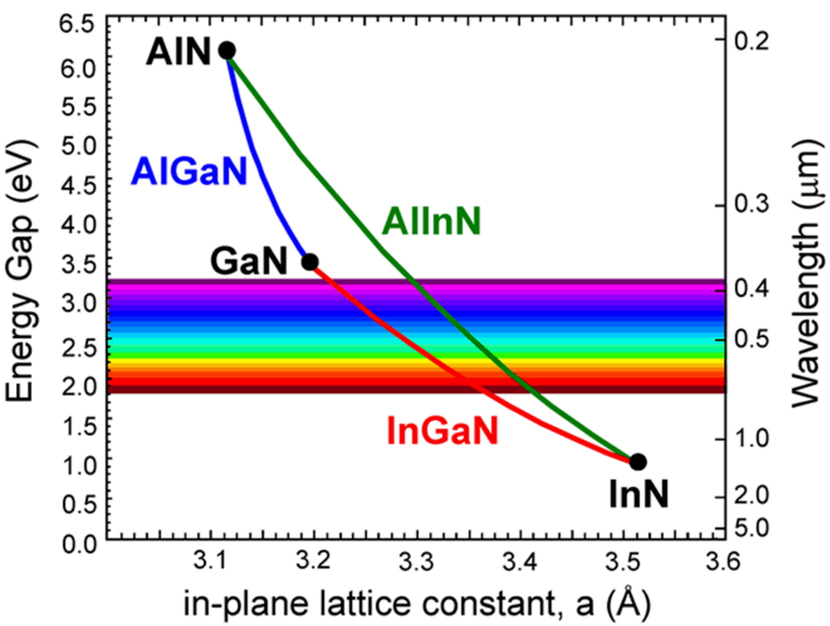


Courtesy: J. Wierer, J. Tsao

Importance of Alloys and Heterostructures

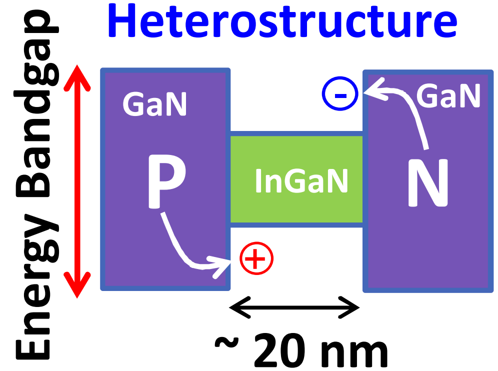
Alloys enable tunable properties and enhanced carrier confinement

Bandgap vs. Lattice Constant

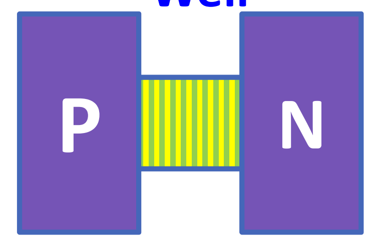


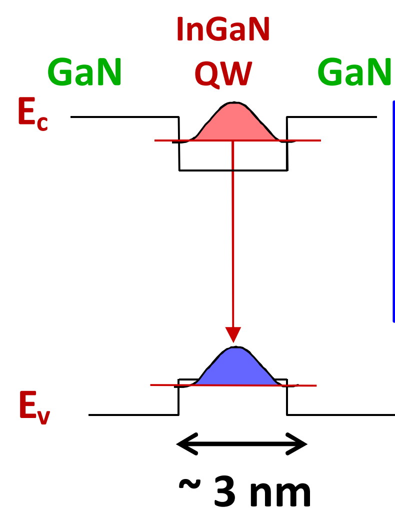
$In_xGa_{1-x}N$: potential for tuning emission through the entire visible spectrum!

Double Heterostructure



Multiple Quantum Well



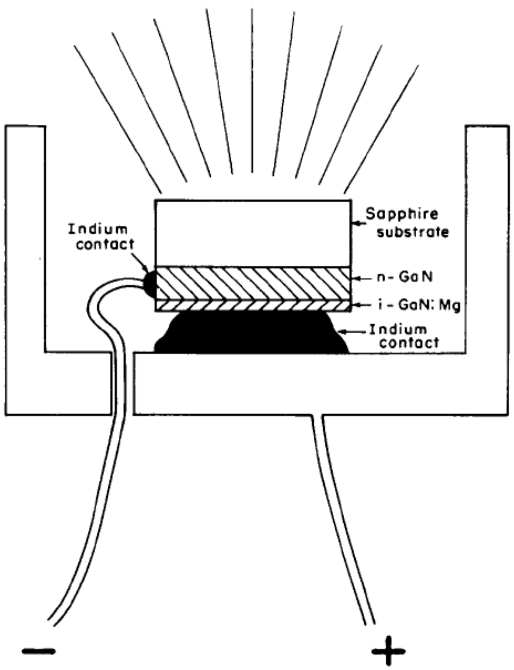


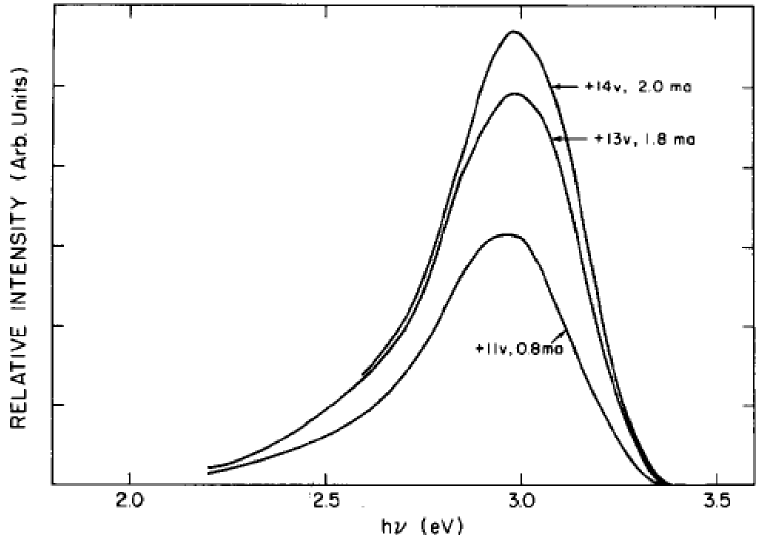
Quantum Wells: Strong spatial overlap of electron and "hole" wavefunctions

→ Efficient light emission

Courtesy: M. Crawford

Early III-Nitride LEDs



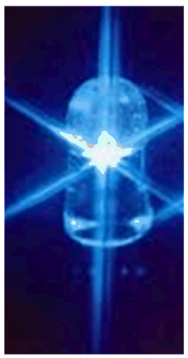


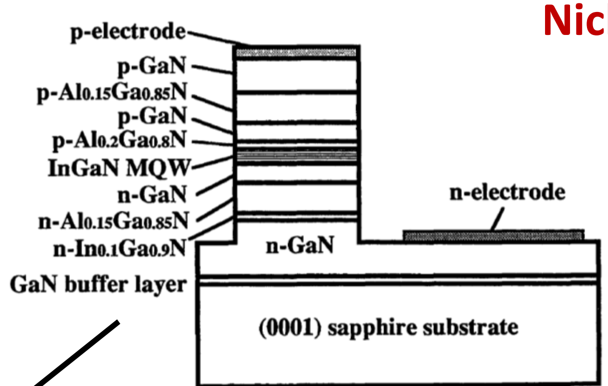
- **J. Pankove and H. Maruska at RCA Laboratories in 1968-74.**
- **First vapor phased growth of GaN.**
- **Produced near blue emission**

Courtesy: J. Wierer, J. Tsao

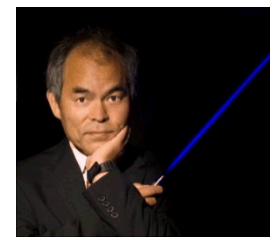
Astounding pace of follow-on breakthroughs

$In_xGa_{1-x}N$:
LEDs across the visible





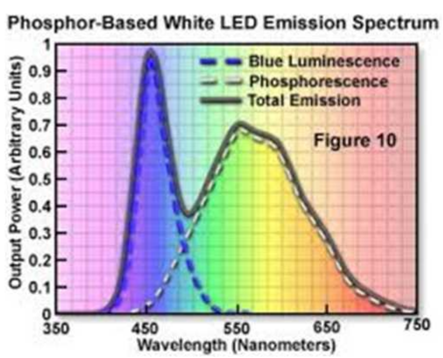
Nichia Blue Laser Diode!
→ > 10,000 hr lifetimes*
→ Blu-Ray DVD (405 nm)



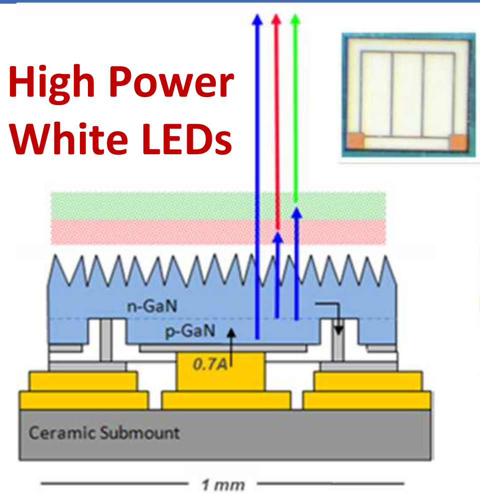
*ZnSe LDs never did achieve high reliability!

1994 1995 1996 1997 1998 …….2007…………………………..2015

First White LED:
Blue LED + YAG Phosphor



High Power White LEDs



Lumileds, OSRAM, Cree, *et al.*

Nakamura's Breakthrough

Candela-class high-brightness InGaN/AlGaN double-heterostructure blue-light-emitting diodes

Shuji Nakamura, Takashi Mukai, and Masayuki Senoh
Department of Research and Development, Nichia Chemical Industries, Ltd., 491 Oka, Kaminaka, Anan, Tokushima 774, Japan

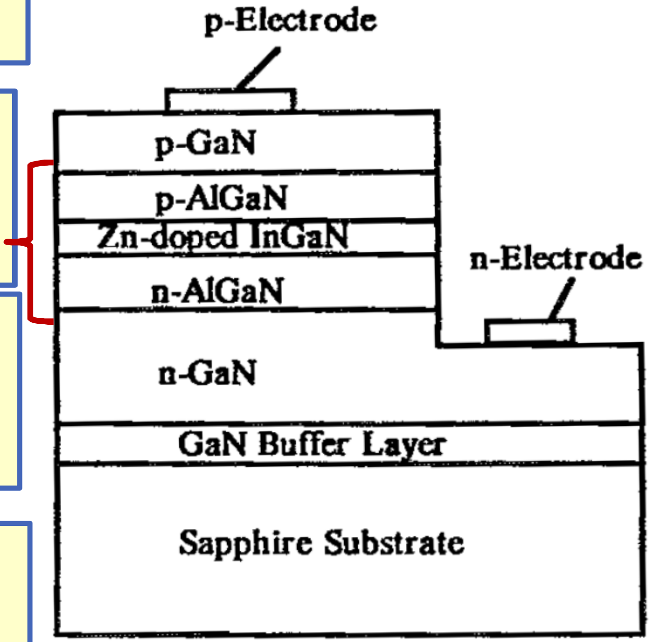
(Received 2 December 1993; accepted for publication 5 January 1994)

Thermally activated P-type GaN

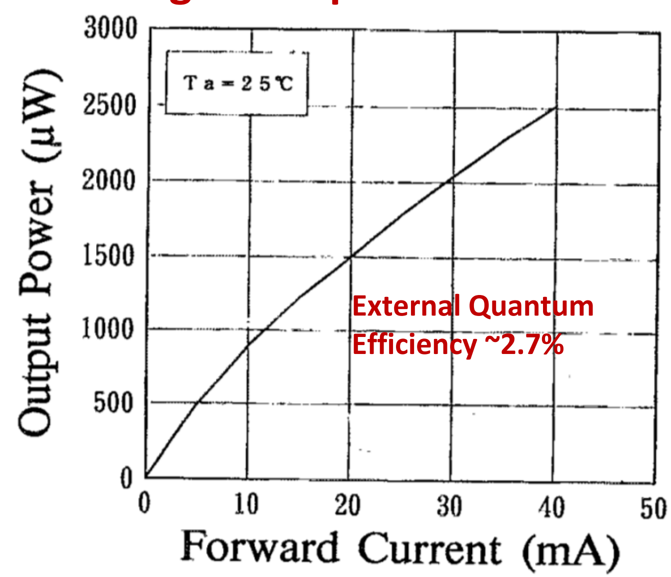
InGaN /AlGaN alloys; Double Heterostructure

Zn-doping of InGaN for enhanced emission

GaN Buffer Layer; improved materials quality



mW level output powers
Highest reported for Blue LEDs



>10X more efficient than ZnSe LEDs but with ~10^5 higher defect densities!??

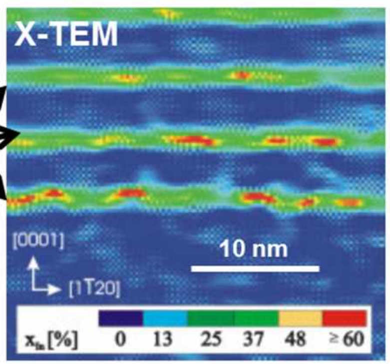
So, why *are* nitrides relatively tolerant of defects?

X **Hypothesis**: Threading dislocations are not non-radiative centers in InGaN

Hypothesis: Carriers are spatially localized in the plane of the quantum well, which reduces their interaction with extended defects

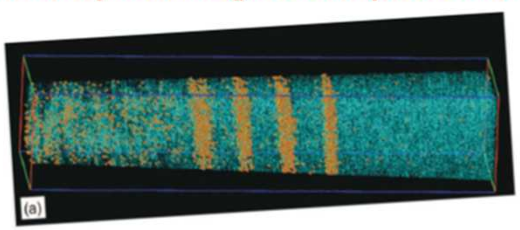
Nanoscale: Indium composition fluctuations

InGaN QWs



But, can easily be caused by e-beam damage!

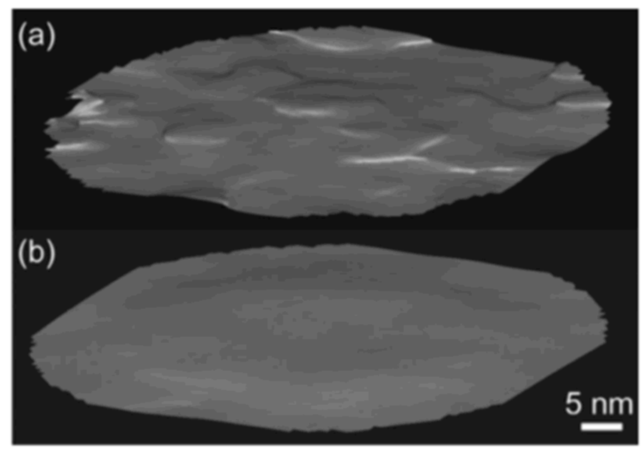
Atom probe of InGaN MQW: InGaN QW is uniform (random alloy with no gross compositional variations)!



...at least for blue and green QWs

Nanoscale: Quantum Well Width Fluctuations

Atom probe of Green QW: iso-concentration surface



Upper QW Interface

InGaN QW

Lower QW Interface

$\Delta E \sim 58$ meV > Room Temp kT (~26 meV)

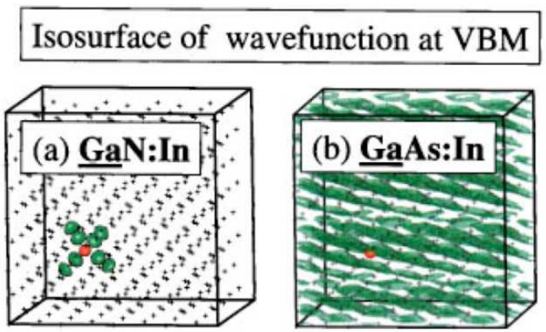
Oliver et al., J. Phys D. 2010

So, why *are* nitrides relatively tolerant of defects?

Hypothesis: Carriers are spatially localized in the plane of the quantum well, which reduces their interaction with extended defects

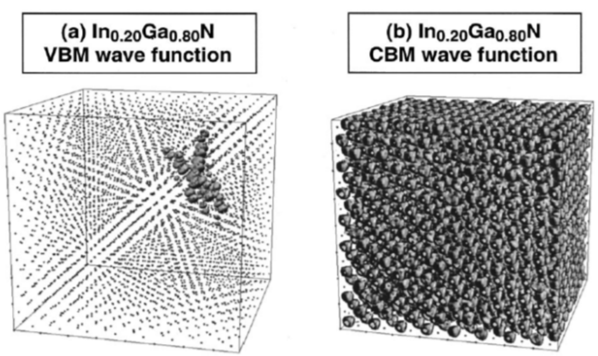
Atomic Scale: Spatially-localized hole wavefunctions

Hole wavefunction for In atom in GaN vs. GaAs



Bellaiche et al. APL 1999

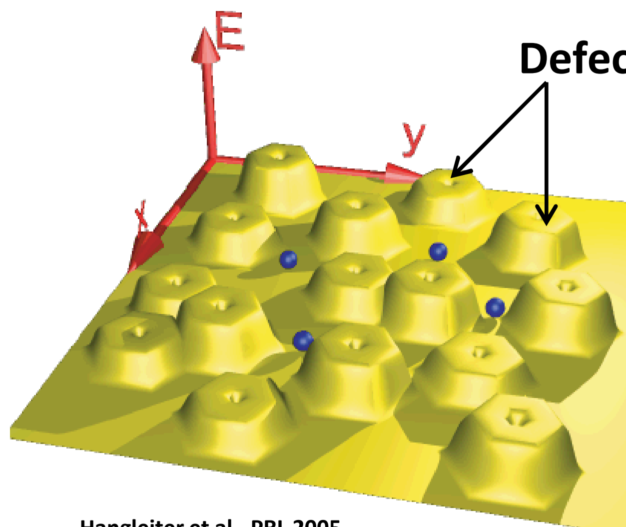
Wavefunctions of uppermost VB and lowest CB states



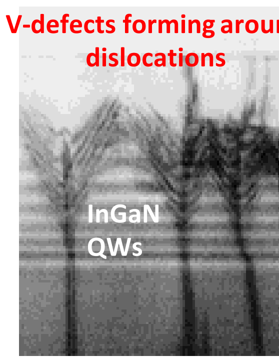
Kent et al. APL 2001

→ Hole localization in random alloy InGaN

Microscale: Screening of Defects



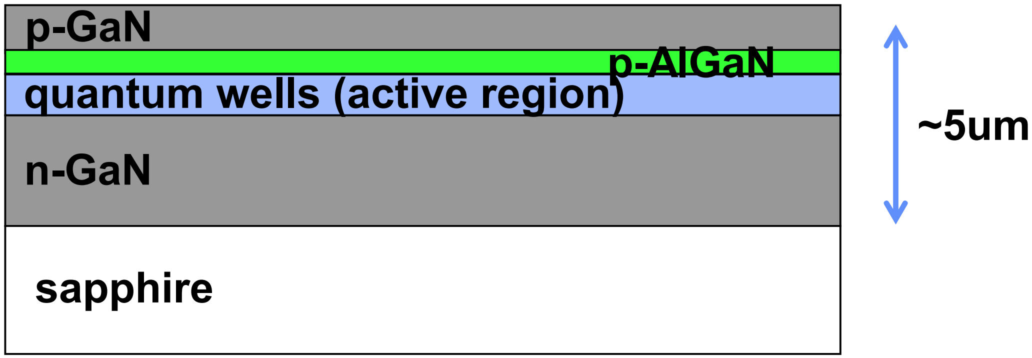
Hangleiter et al., PRL 2005

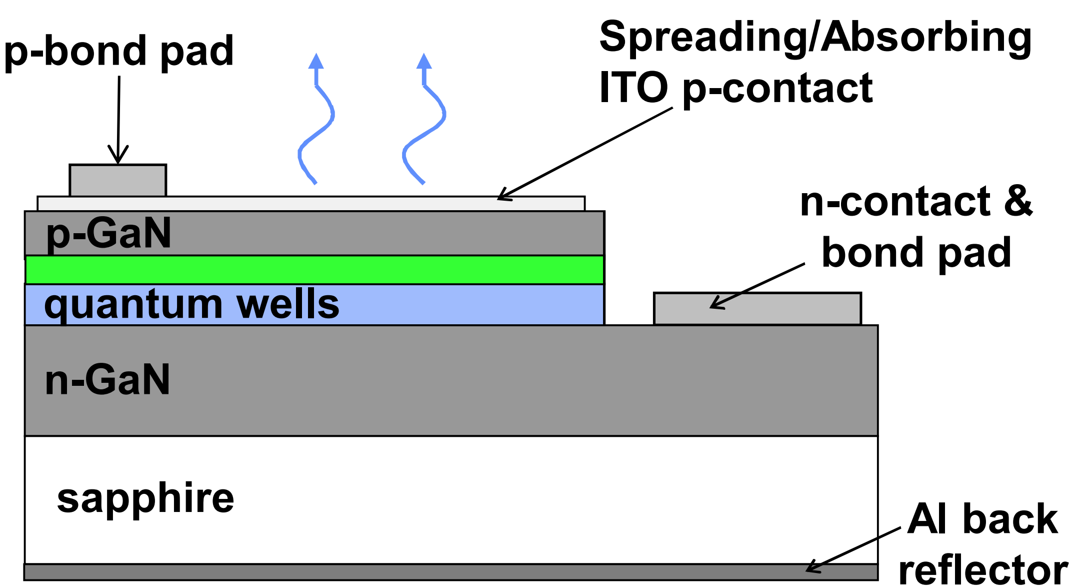


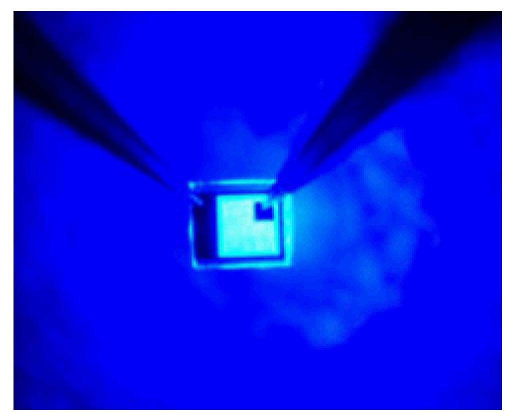
Scholz et al., PSSA 2000

Proposed microstructure for shielding defects:
- "V-defects" around dislocations
- Change of QW composition or thickness in proximity of dislocation

Anatomy of an blue III-nitride LED



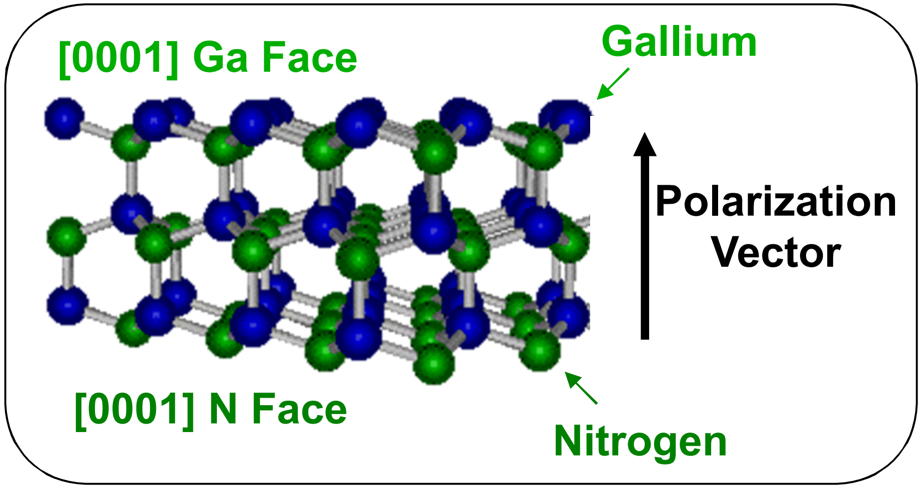




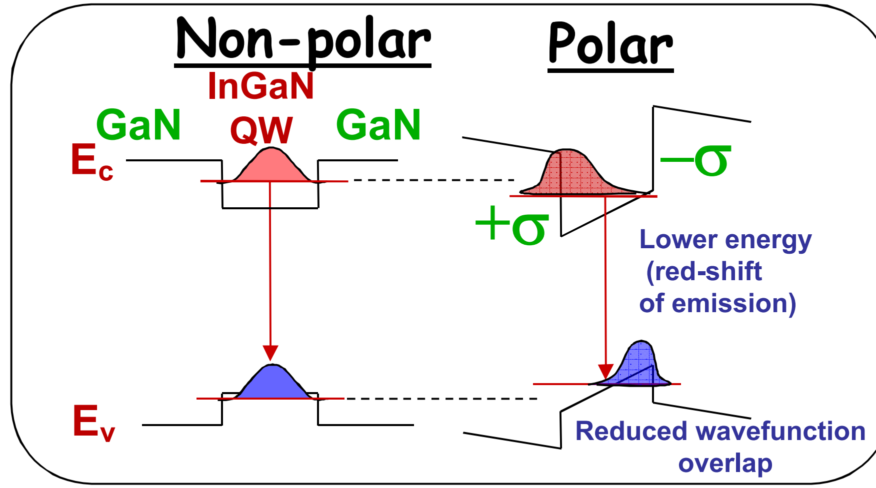
Courtesy: J. Wierer, J. Tsao

Polarization effects in InGaN LEDs

Hexagonal (Wurzite) GaN crystal structure



Effect on InGaN quantum well



- Dominated by piezoelectric (strain-driven) polarization for InGaN QWs on GaN
- Internal E-fields cause reduced electron-hole overlap → reduced radiative efficiency
- E-fields shift emission to <u>longer wavelengths</u>; → blue-shifts with current
- Significant band-bending creates barriers to carrier flow and/or reduced carrier confinement

Full LED structure

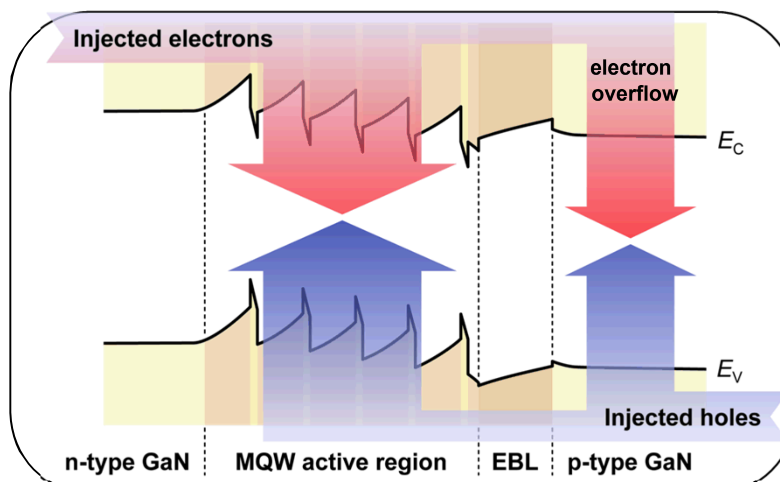
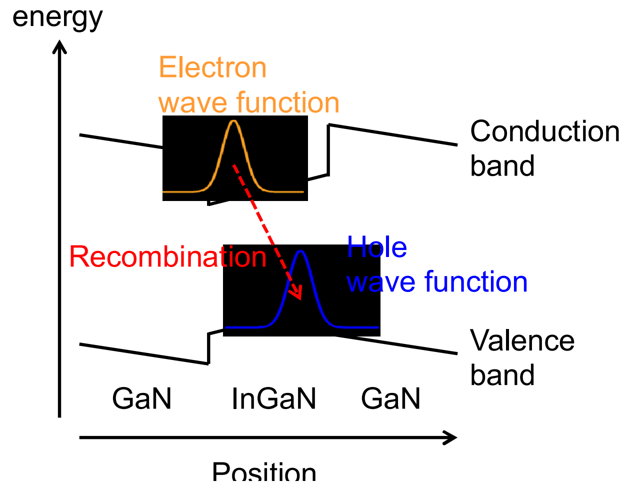
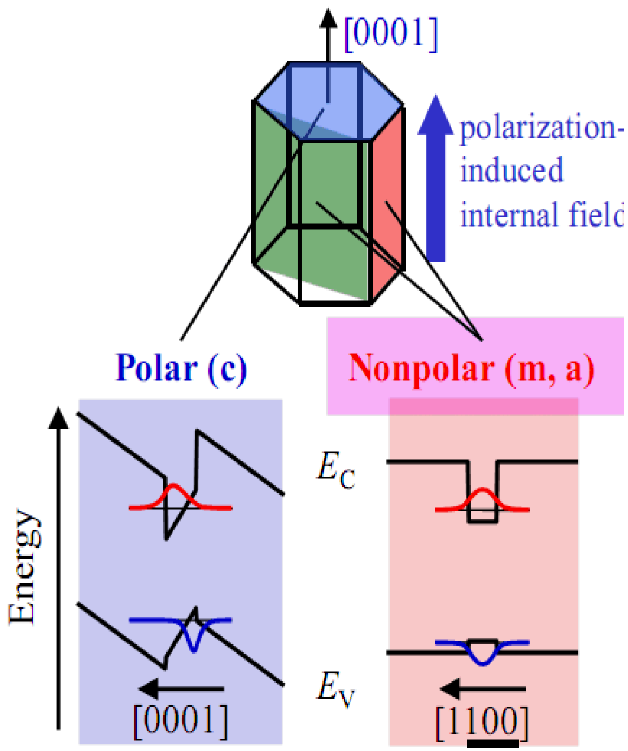
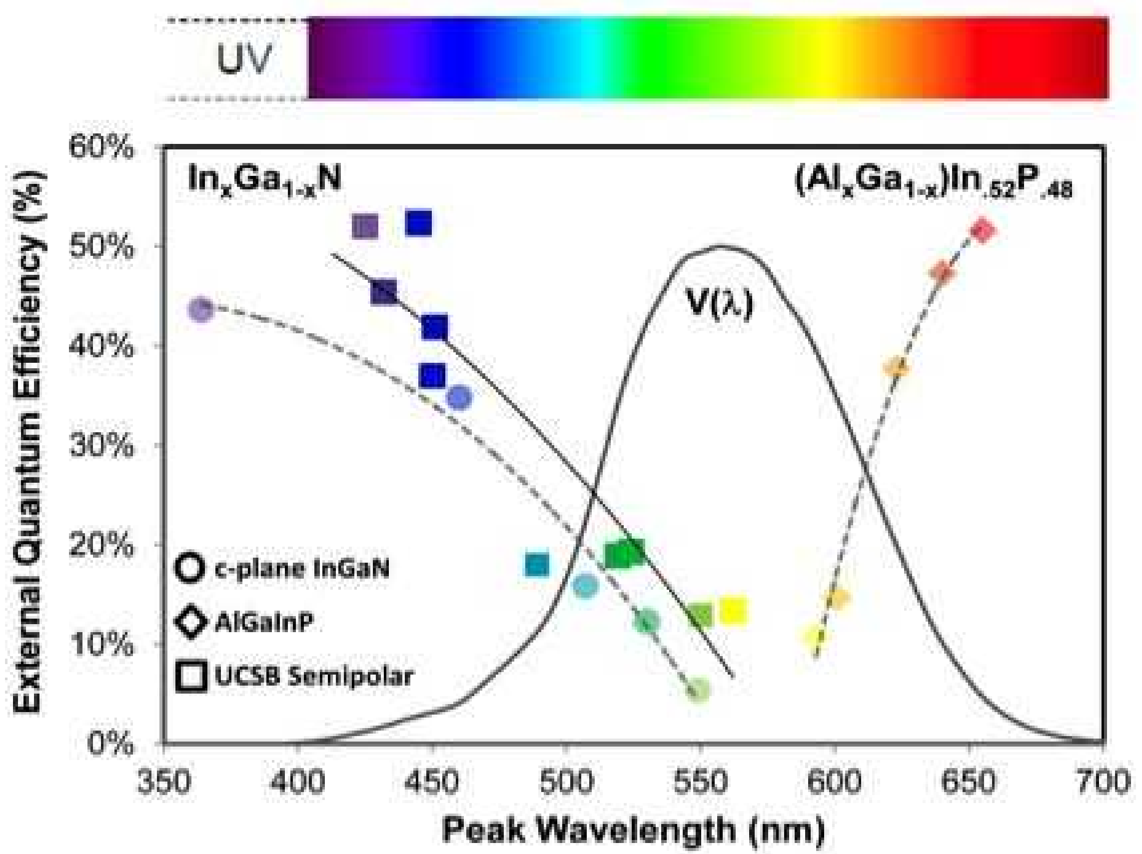


Figure: E. F. Schubert (RPI)

The “Green Gap”

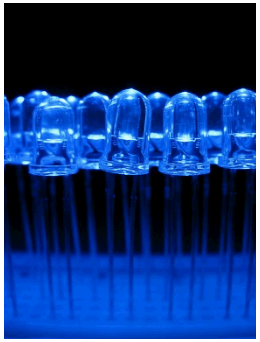


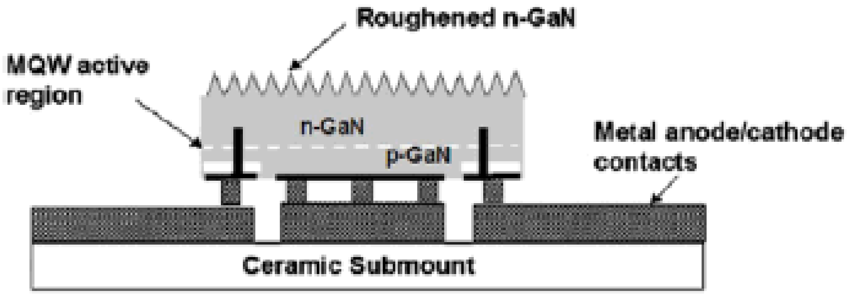


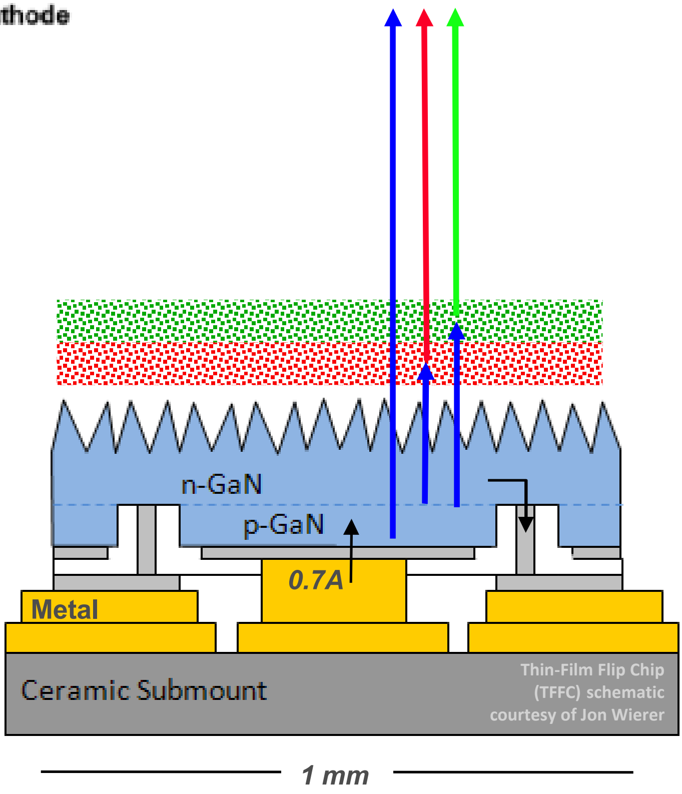


The Anatomy of a White LED

Blue LED



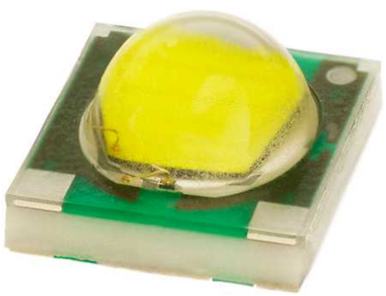




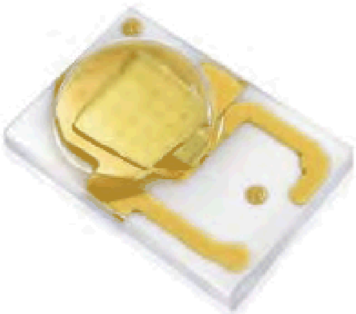
Where do we get the other 2 colors?
We use 2 phosphors for green and red

Y.S. Lin and J. A. Yeh, Appl. Phys. Express, vol4, p092103, 2011

Cree

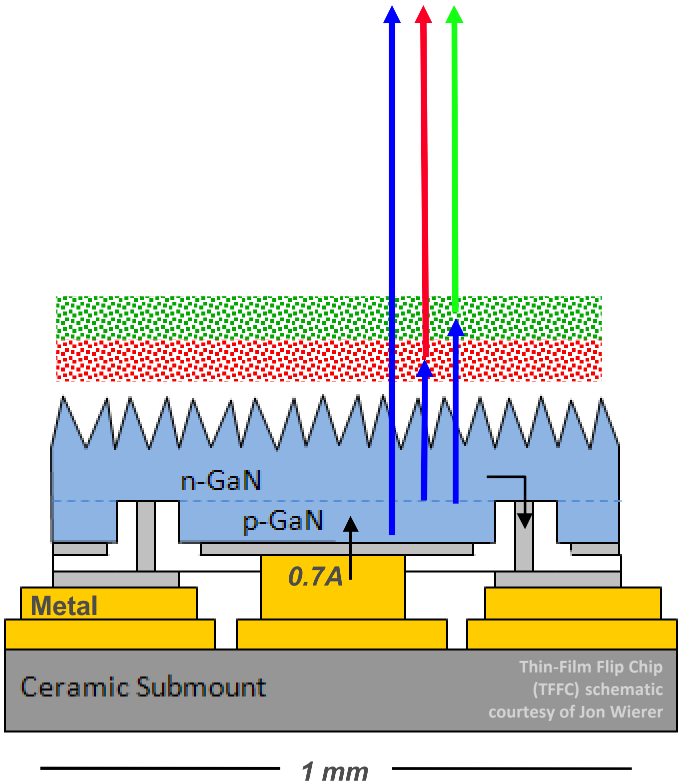


Lumileds



How Can We Improve the Efficiency of Solid State Lighting?

78%
Spectral efficiency
(match to human eye)



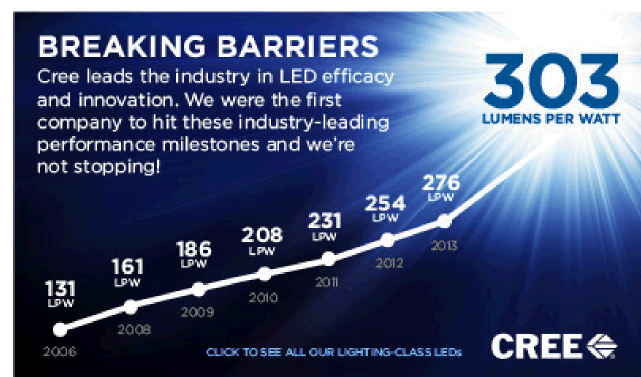
54%
Phosphor
(and package)
efficiency

38%
Blue LED
efficiency

Thin-Film Flip-Chip Architecture

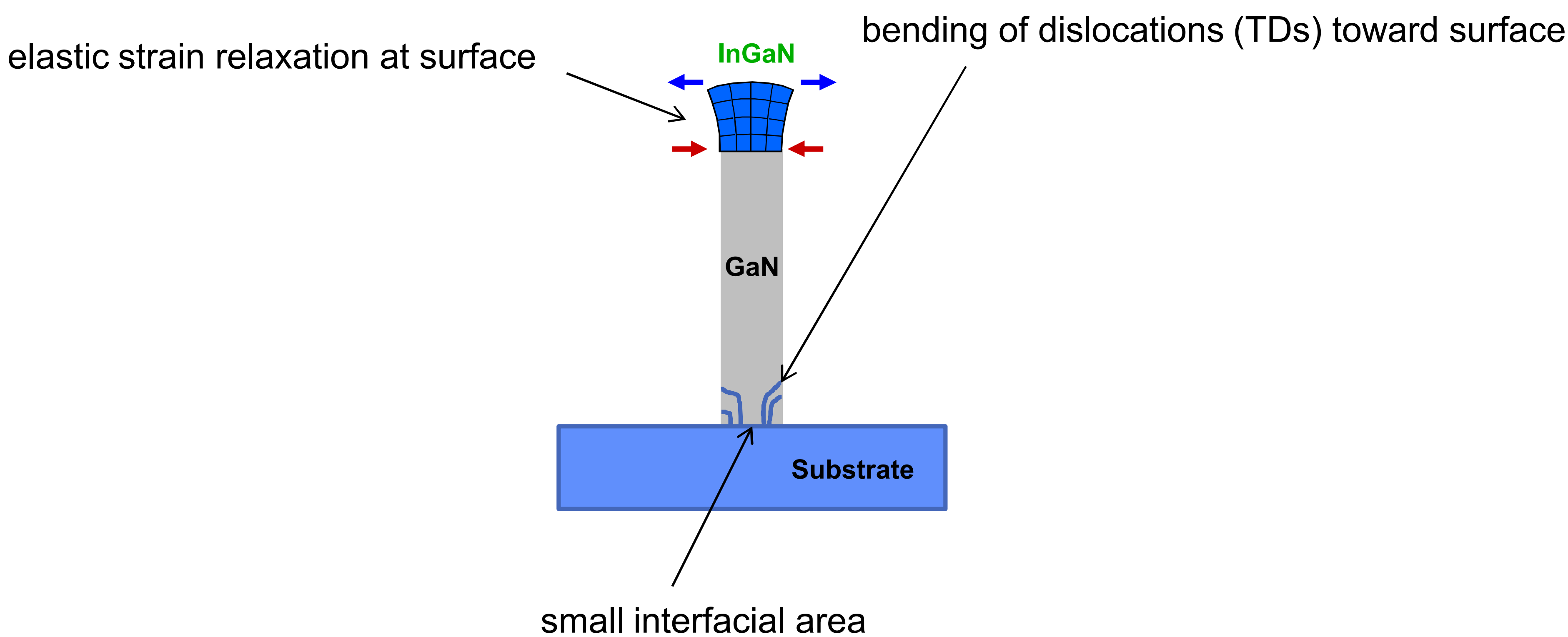
16%
Overall efficiency
(luminous efficacy η_φ = 66 lm/W)

@
Color rendering index (CRI) 85
Color temperature (CCT) 3,100 K
Current density 70 A/cm²



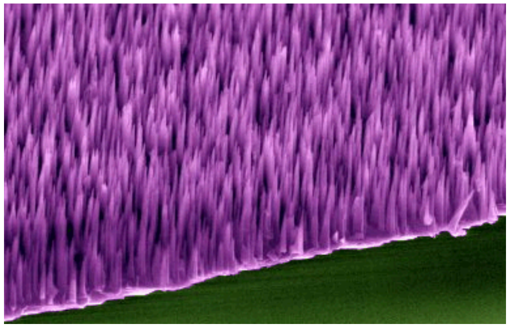
Nanowire Lasers

Why Nanowires Are a Good Idea

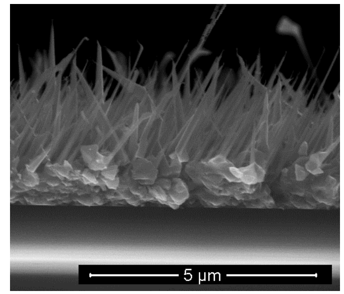


Nanowires

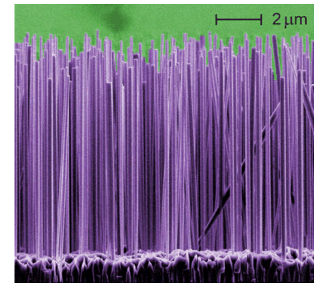
Nanowires can be grown (“bottom up”):



GaN NWs Sandia

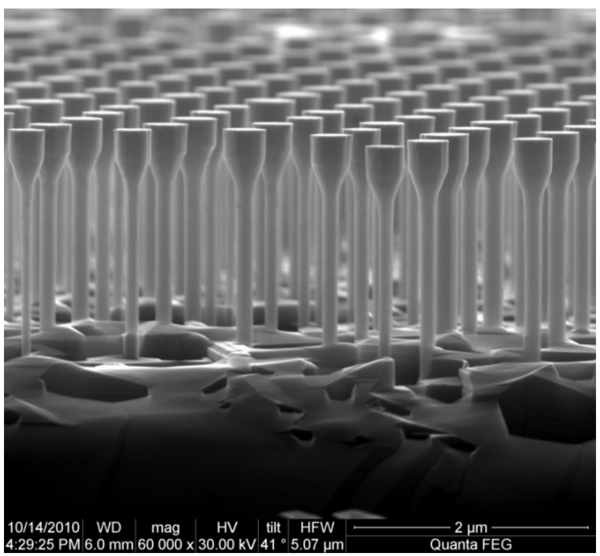


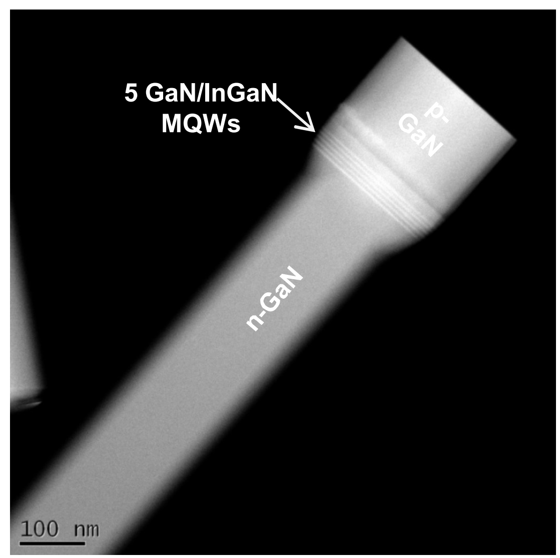
GaN NWs on tungsten foil - Sandia



GaN NWs on Si - NIST

Nanowires can be fabricated (“top down):

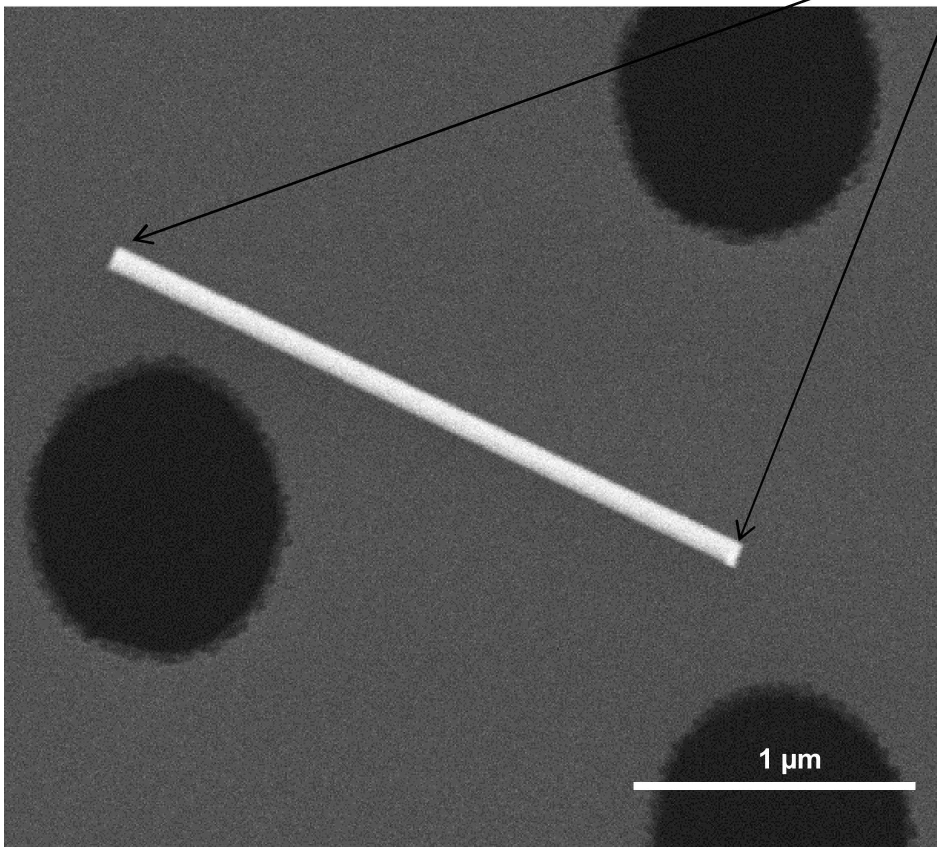


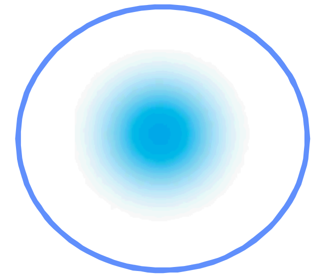


“nano LED”

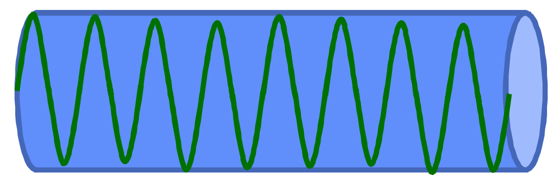
Nanowire Lasers

Two end-facets act as the mirrors

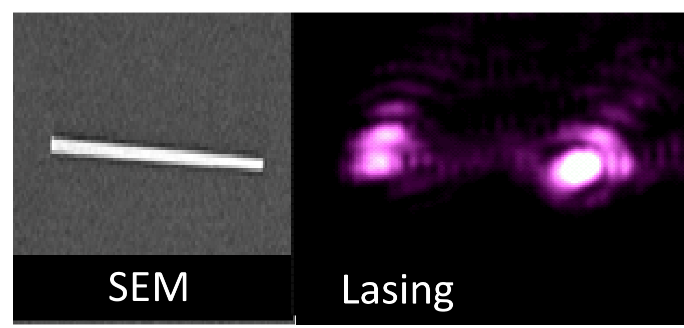




Light is confined in the cross-section

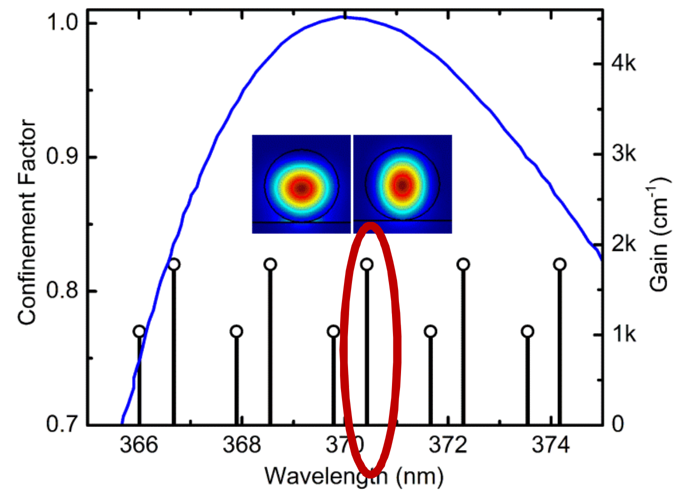


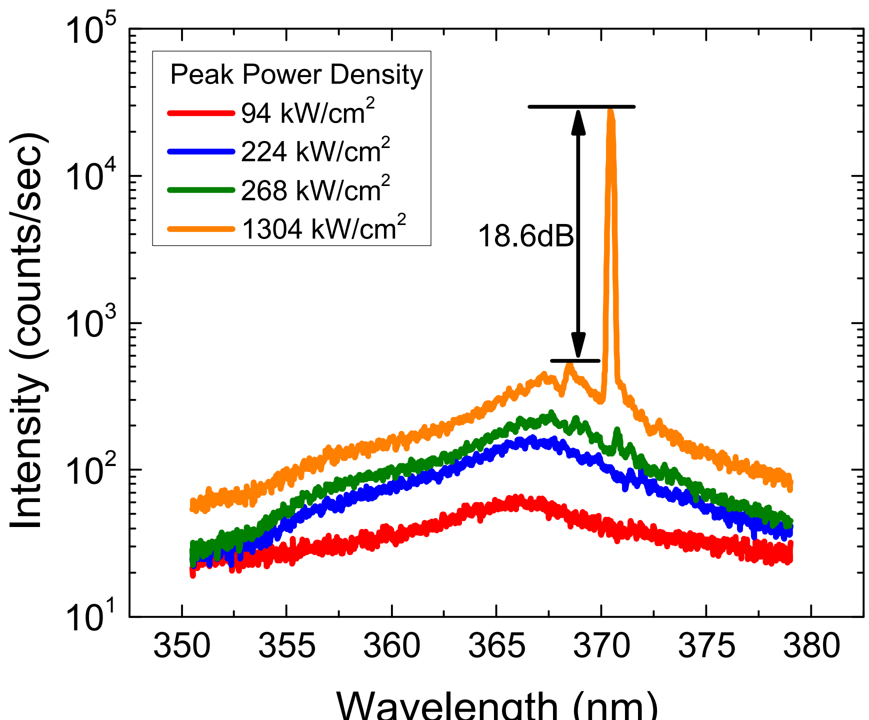
Light oscillates along the length of the nanowire



Nanowire Lasers – Achieving single-mode

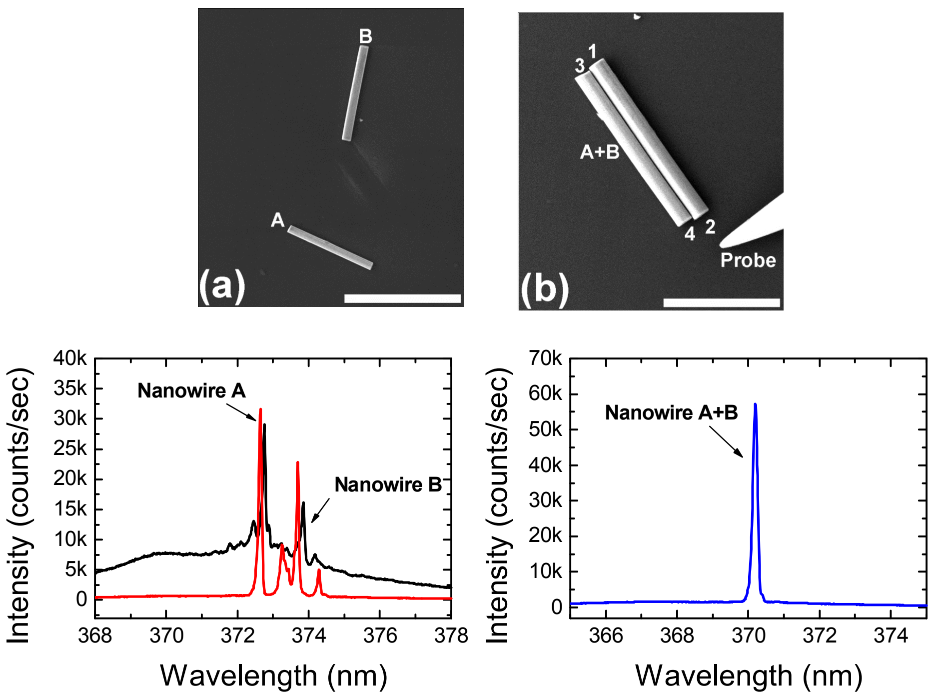
- **Very small cavities**
- If a laser is made small enough, there is only one possible lasing mode
- GaN nanowires can come very close to these small dimensions
- Due to the strong mode competition in such small lasers, only one mode reaches a lasing threshold





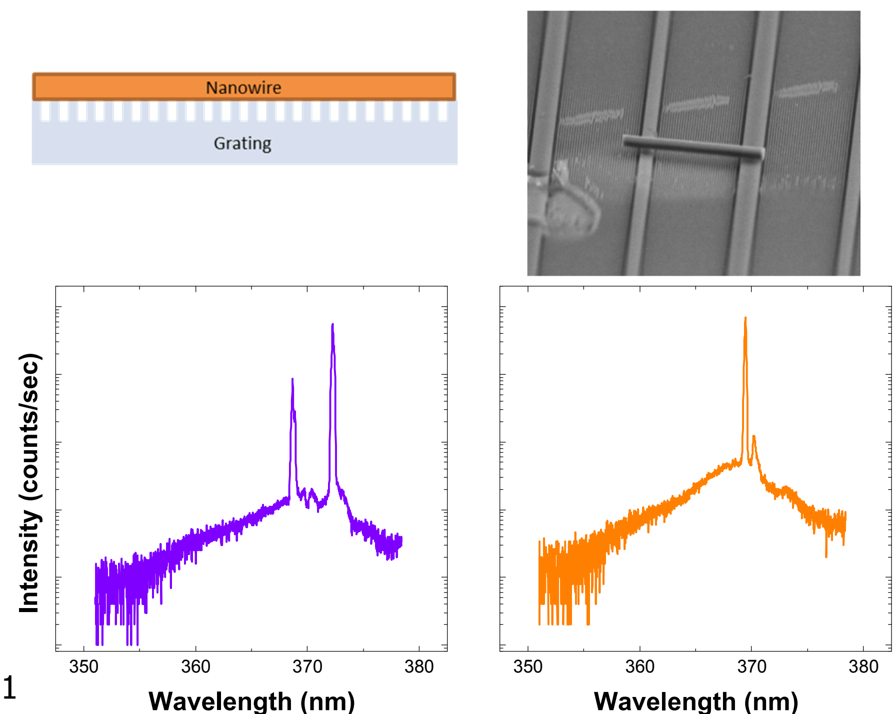
Nanowire Lasers – Achieving single-mode

- **Coupled nanowires**
- Two nanowires separated act as individual lasers
- When brought together they act as a single laser with only one lasing mode



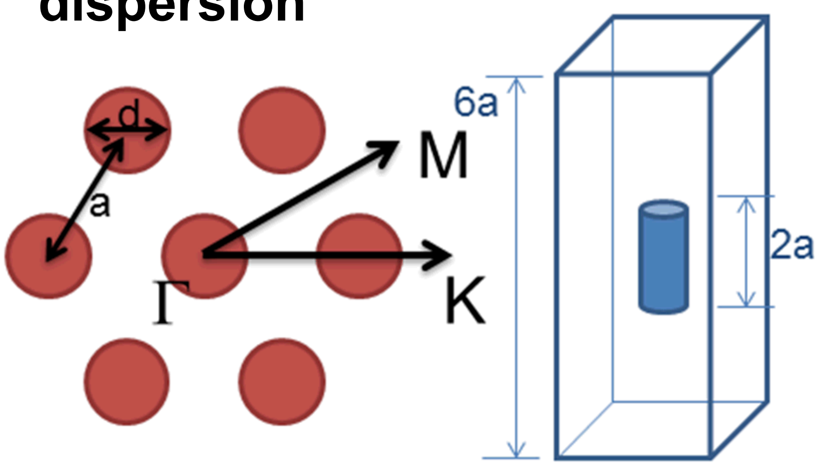
Distributed feedback

- Small reflections are placed along the entire cavity
- A reflection band is formed
- Single mode lasing occurs near the reflection band

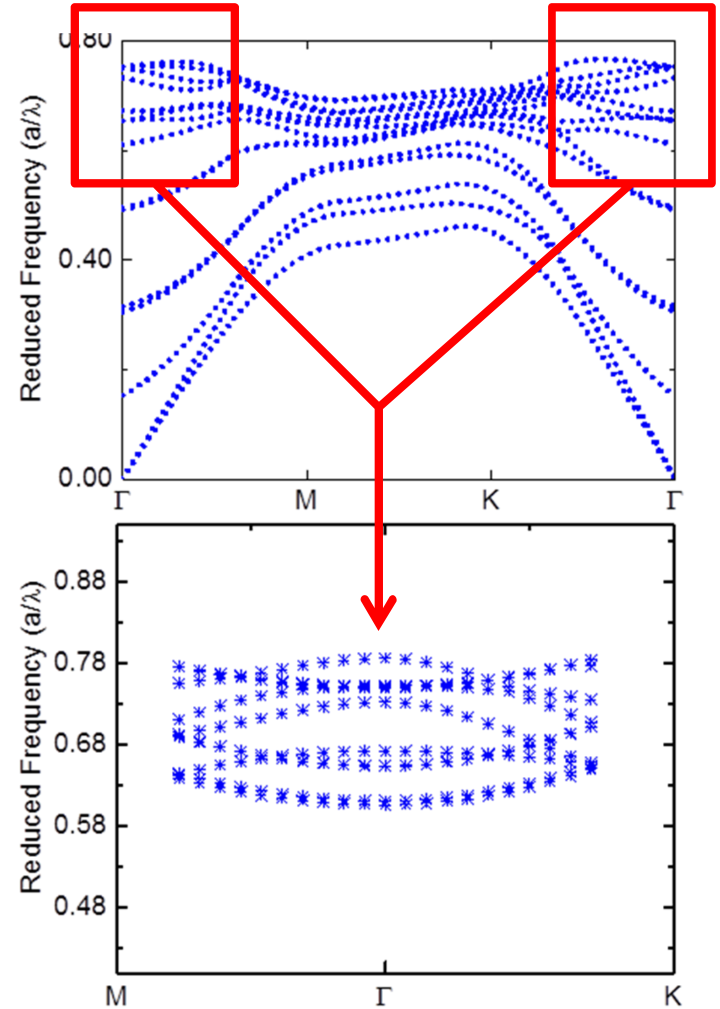


Designing vertically emitting photonic crystal lasers.

- We desire low group velocity
  - enhances the light matter interaction
  - forms standing waves within the gain medium
  - First described by Sakoda (1999)
- We designed high order bands designed to have low dispersion

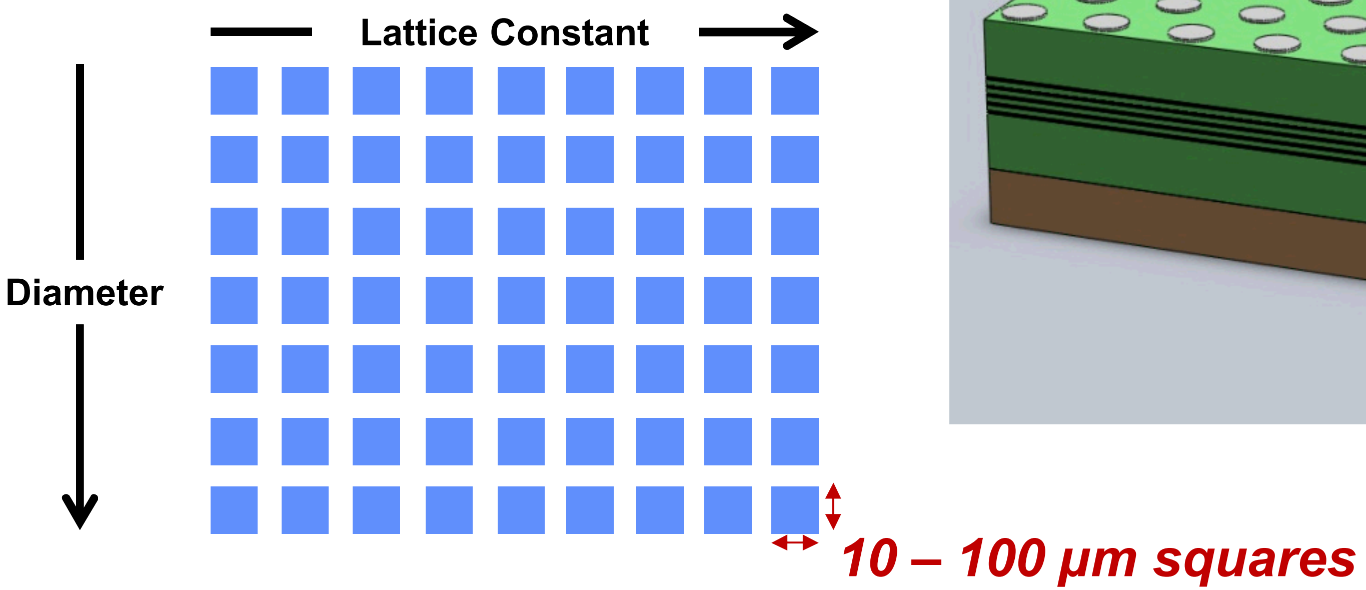


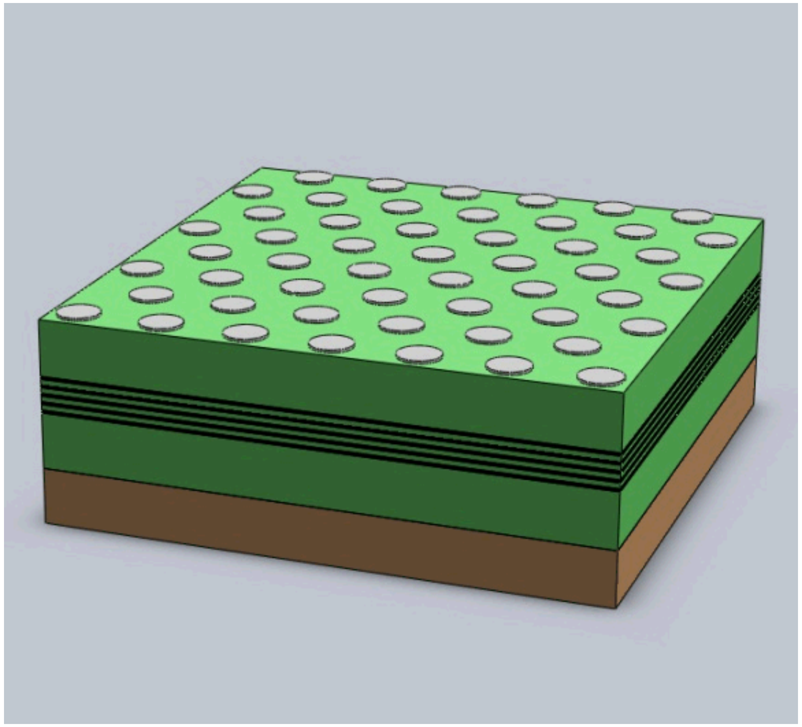
Plane Wave Expansion Super Cell



Fabrication | Patterning of 2DPC using e-beam

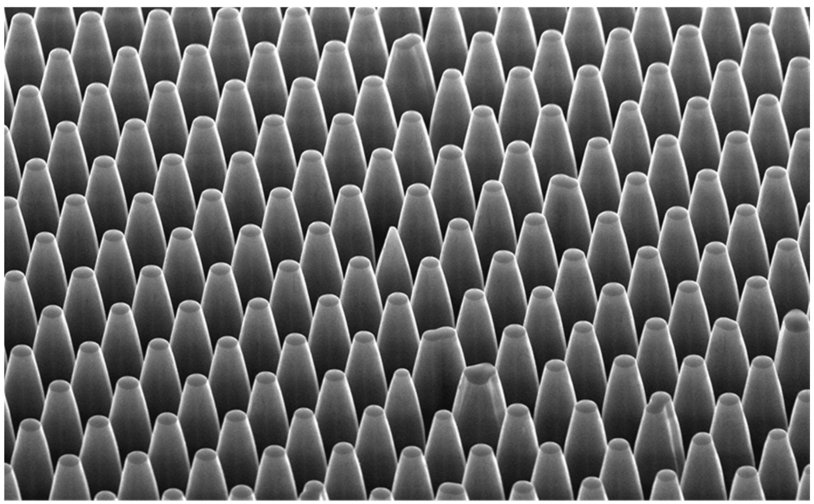
- E-beam Patterning
- Triangular Lattice of Ni Dots
- 9x7 array

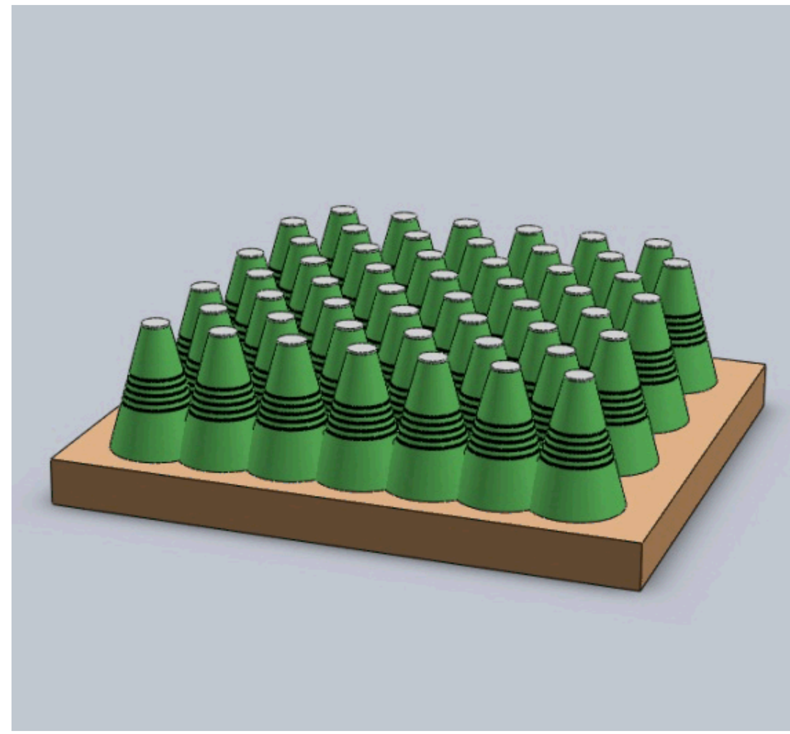




Fabrication | top-down 2-step etch process

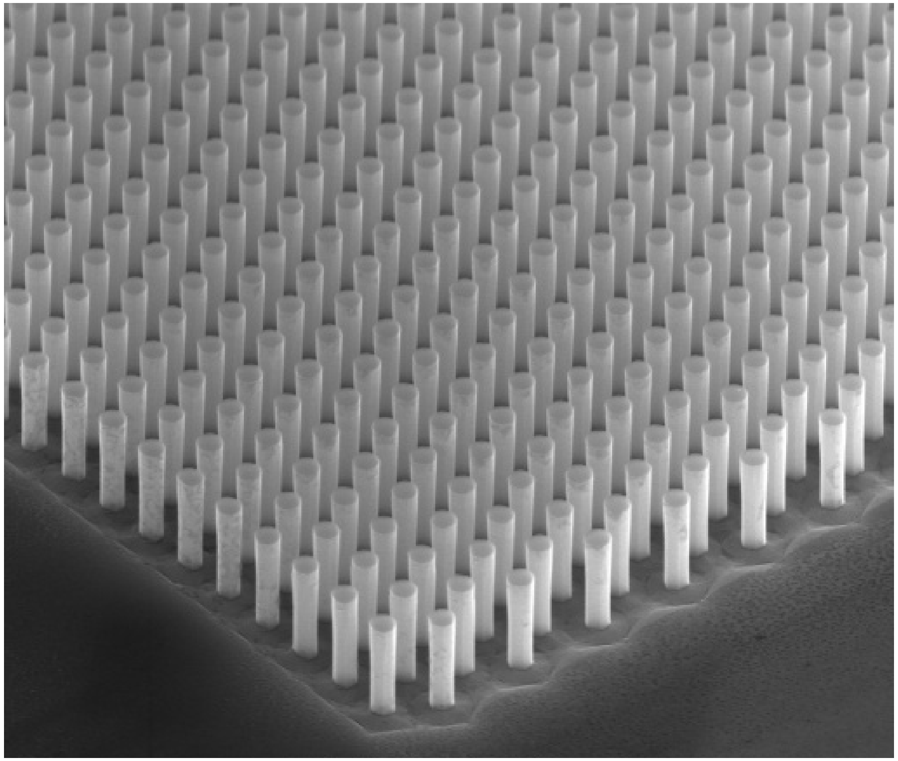
- Same process as our top-down nanowires
- Dry (ICP) followed by wet (KOH) process

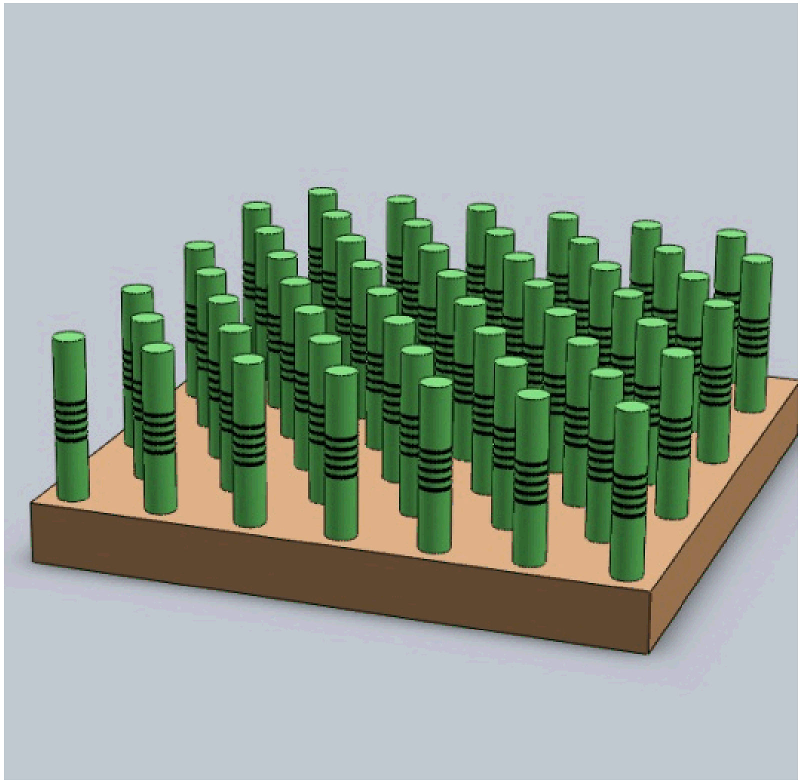




Li, Q. *et al. Optical performance of top-down fabricated InGaN/GaN nanorod light emitting diode arrays. Opt. Express 19, 25528-25534 (2011*
Li, Q. *et al. Single-mode GaN nanowire lasers. Opt. Express 20, 17873-17879 (2012).*

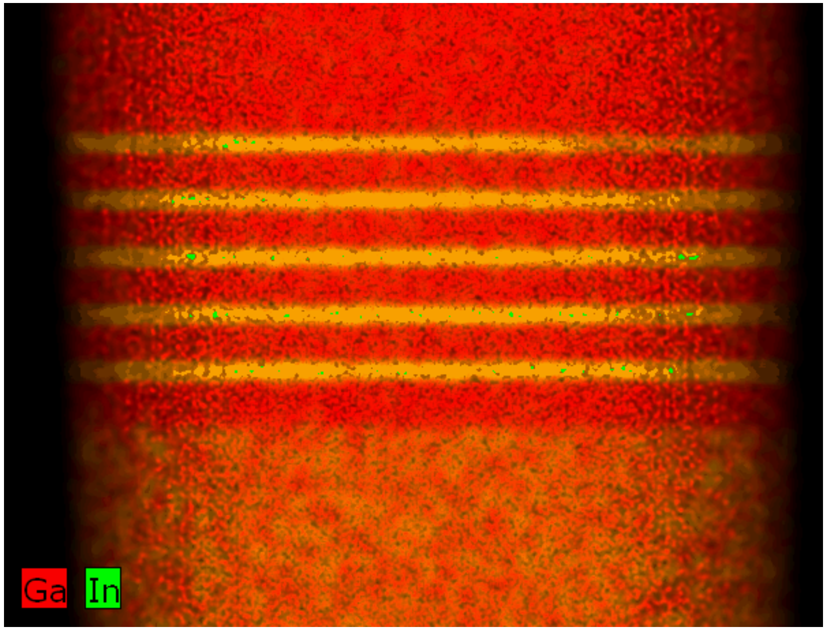
Fabrication | Ordered arrays of anisotropic nanowires

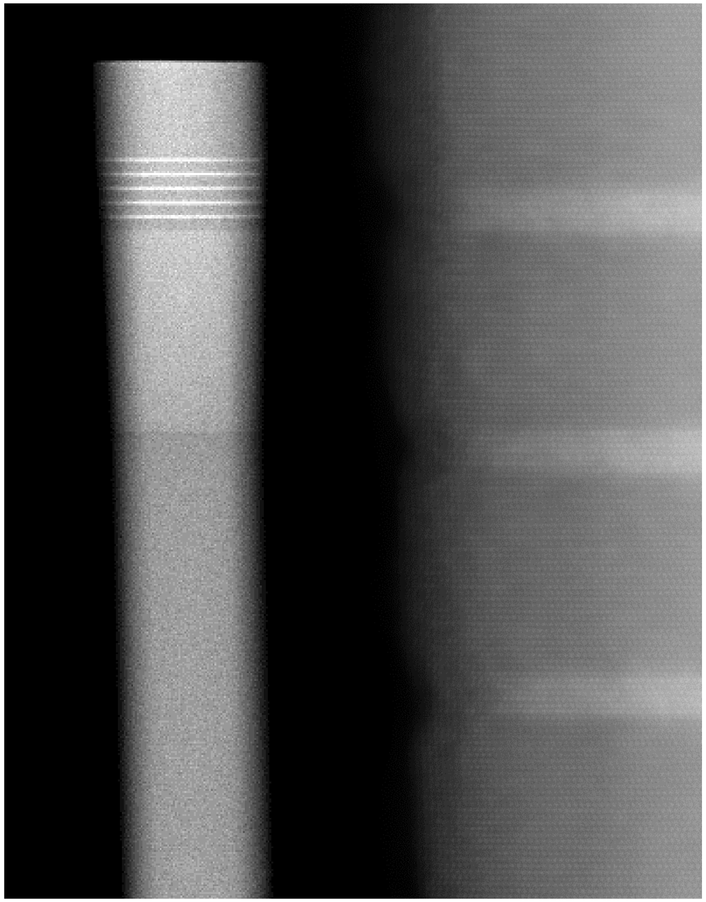




TEM of a single nanowire taken from an array

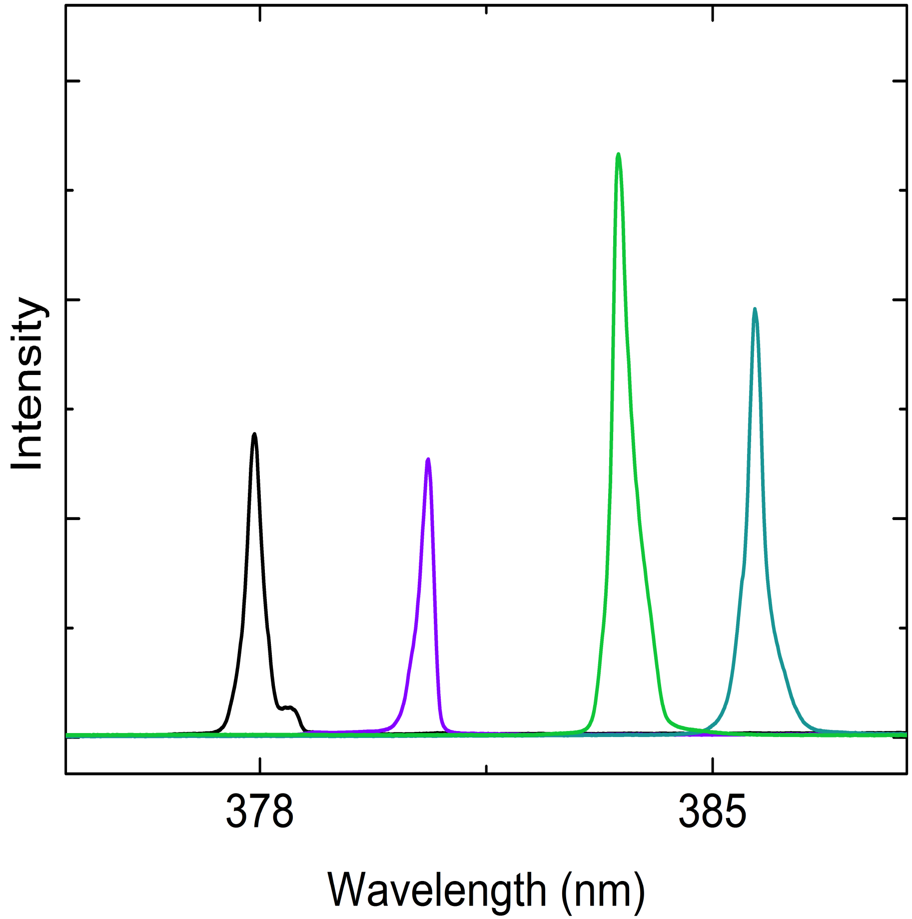
- 5x MQW InGaN Emission Centered at 430nm
- 2% In underlayer
- Slight taper from the InGaN quantum wells

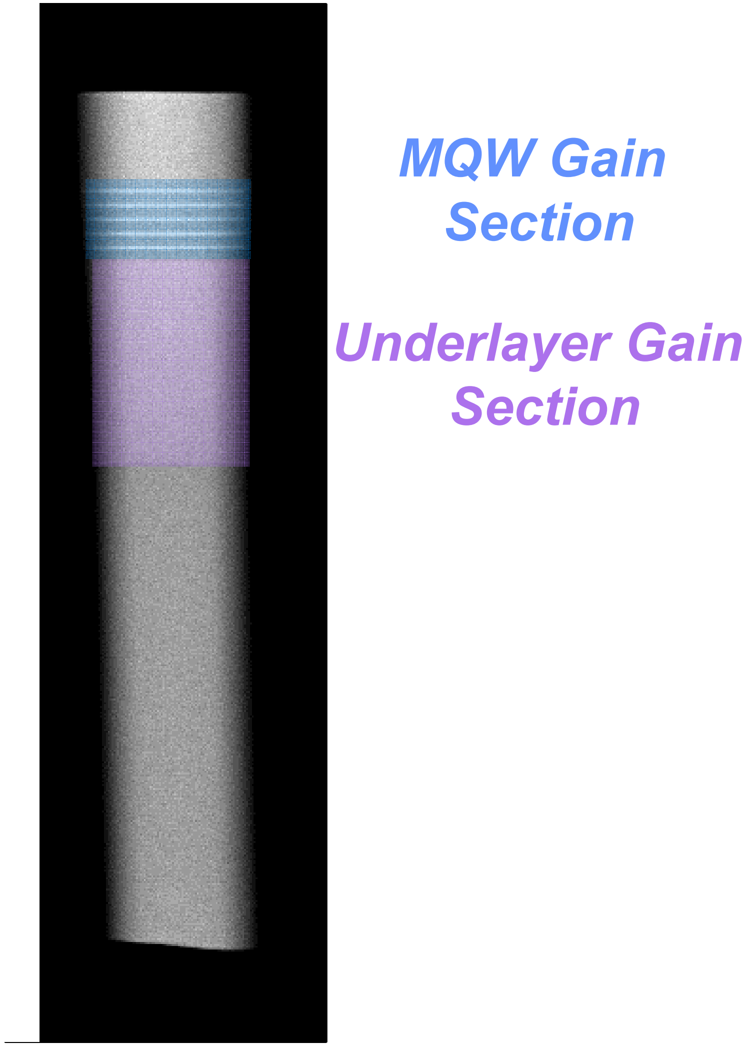




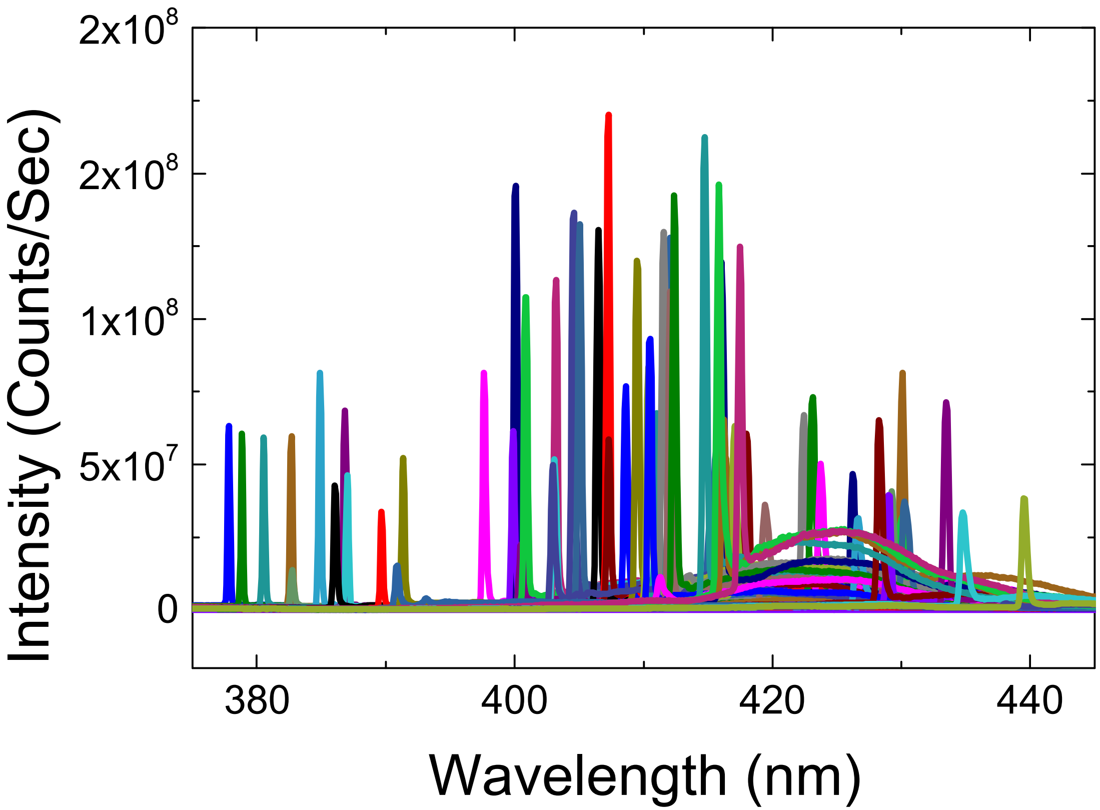
Ping Lu, Sandia

Gain from multiple sections

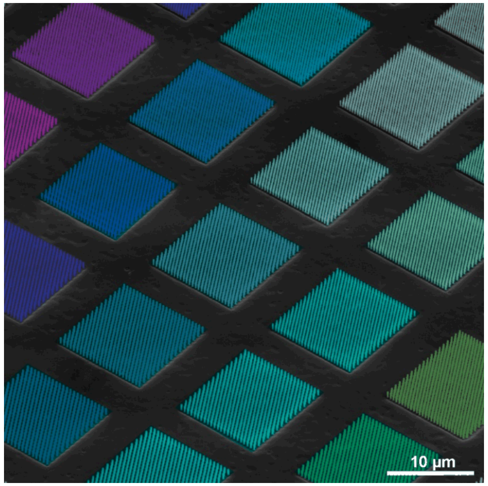




Multi-color Laser Array



- Spectral Coverage from 380-440nm.
- Thresholds are reasonable compared to other optically pumped III-N nanowire devices. (<500kW/cm^2 for all devices)



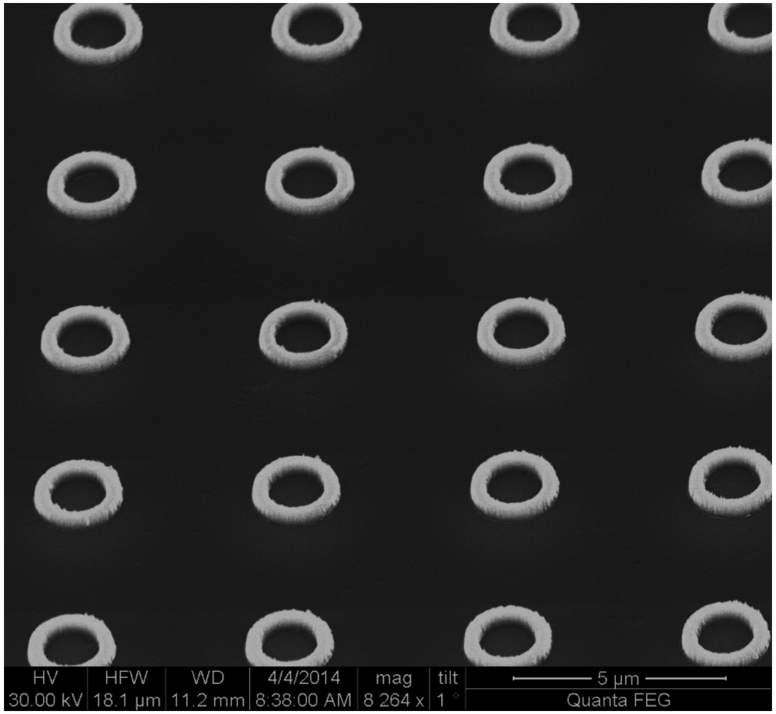
Other geometries for top down nanolasers

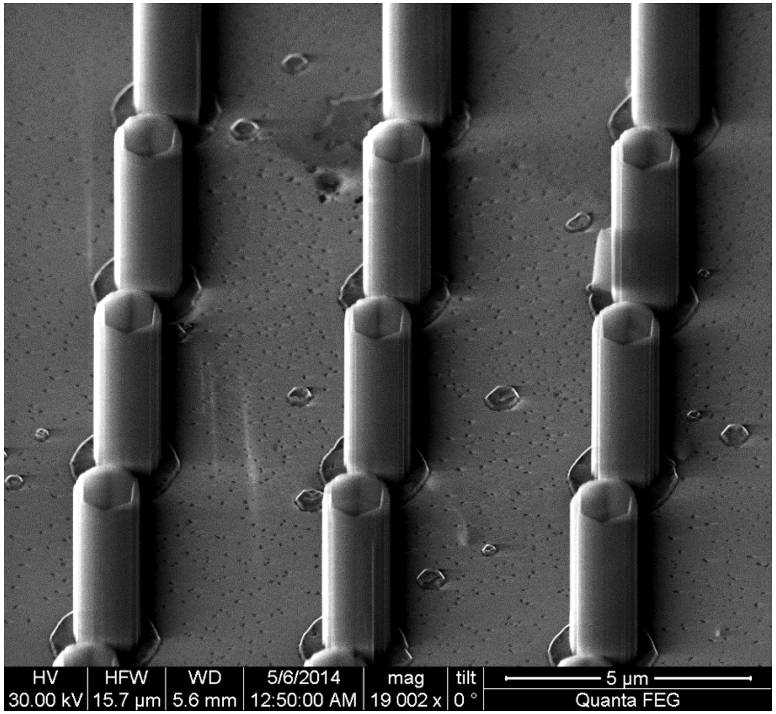
Nanotubes

“Ridges”

Etc

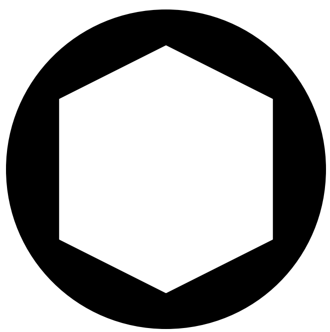
GaN Nanotube Lasers



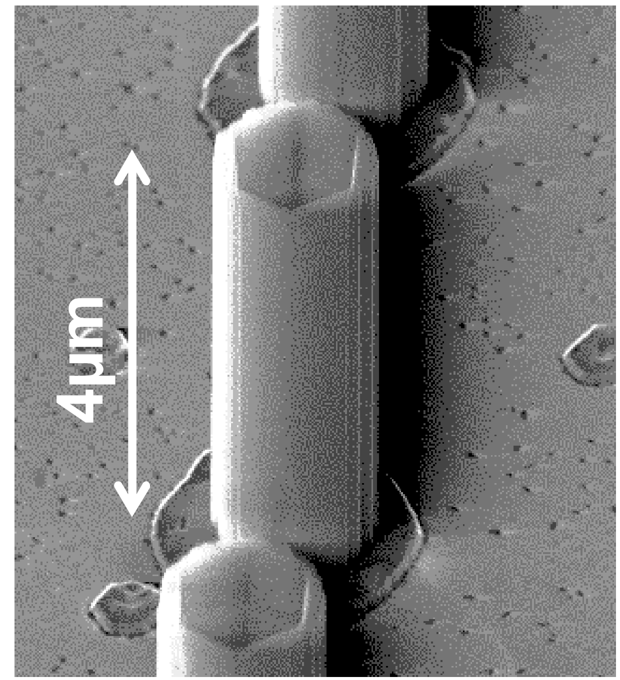


Fabricated GaN nanotube

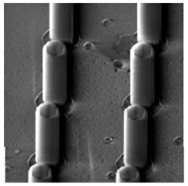
- **Length:** 4μm
- **Outer Diameter:** 1.3μm
- **Thickness:** 150nm

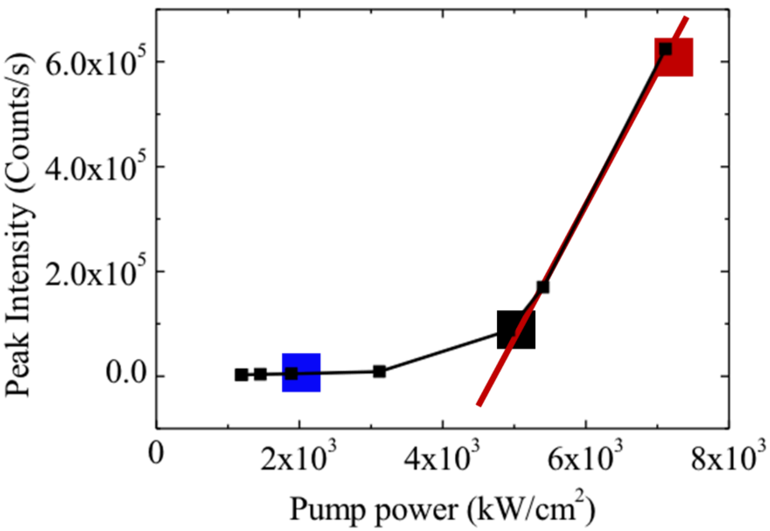


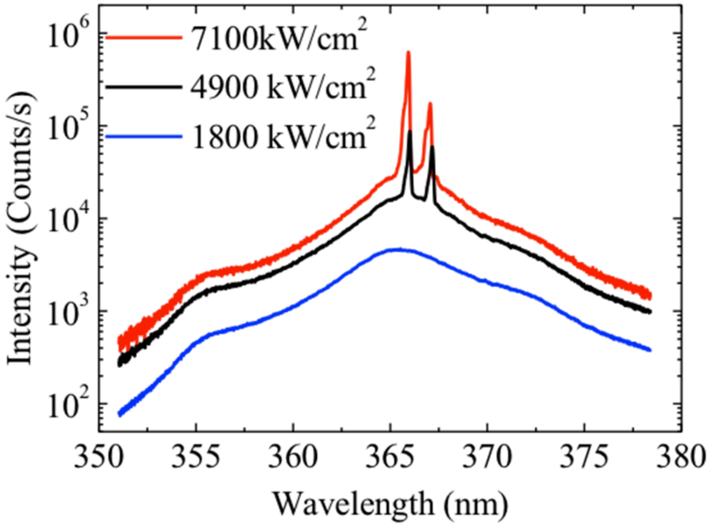
Hexagonal opening



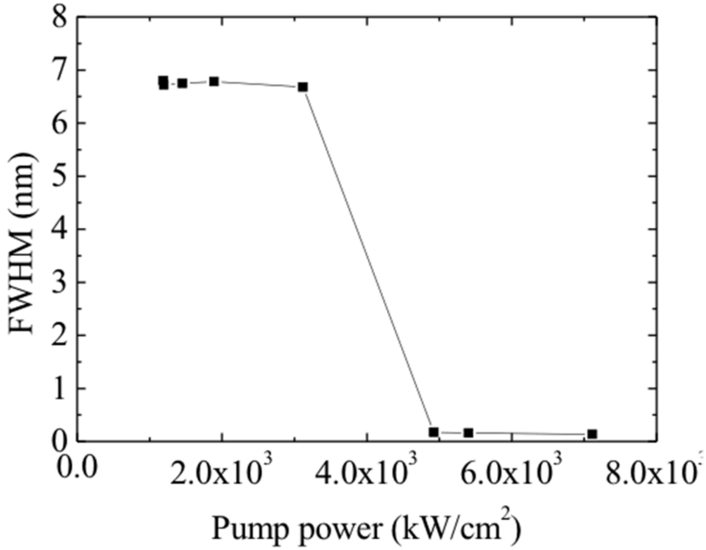
Lasing Spectra and L-L Curve







Threshold pump density = 4600kW/cm^2

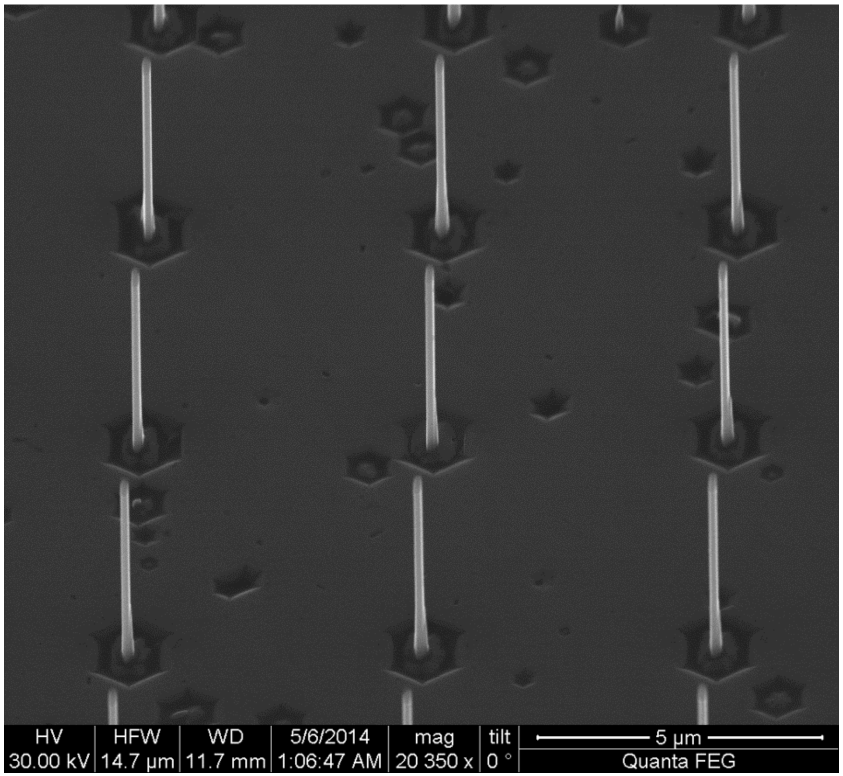


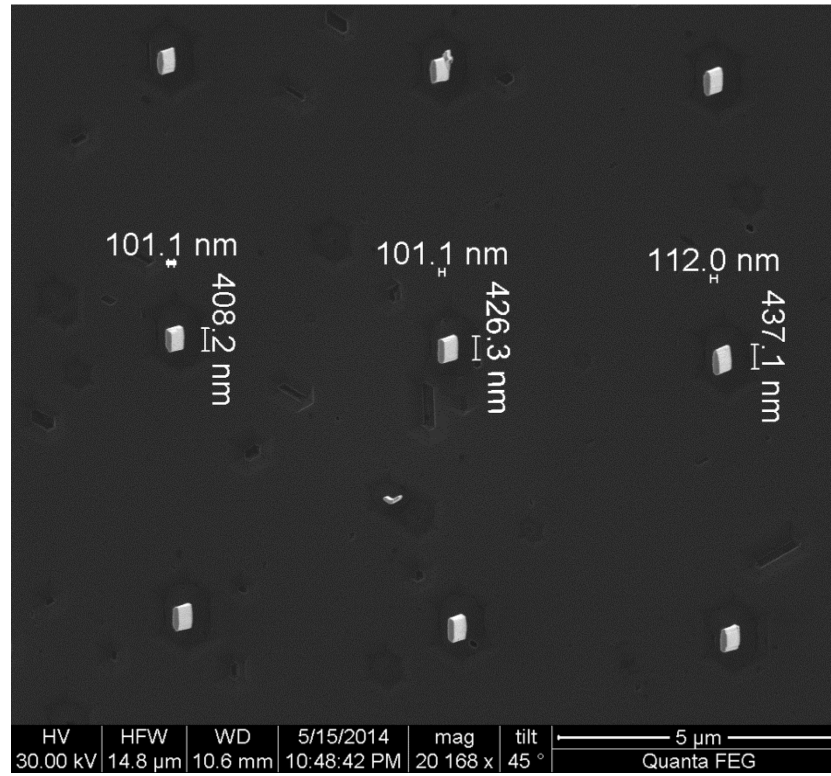
FWHM decreases to 0.13nm as the nanotube laser is pumped above threshold

FWHM is limited by the resolution of the spectrometer

Sandia National Laboratories

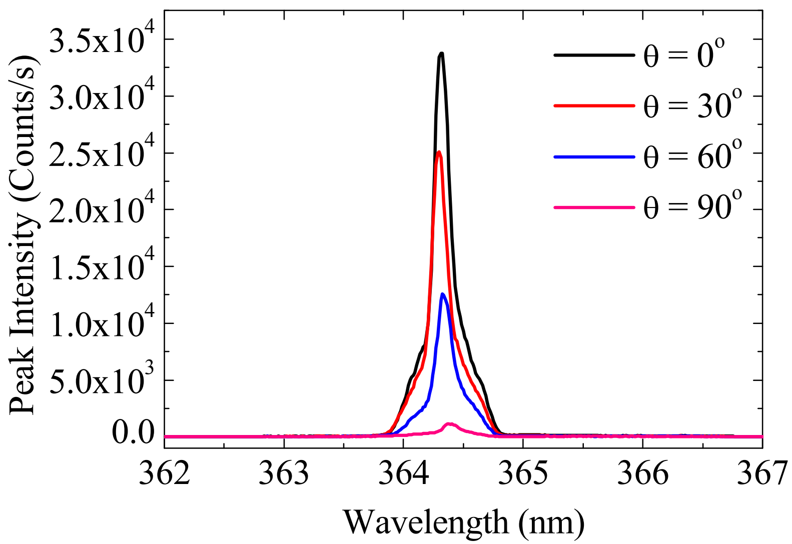
SEM images of <u>rectangular</u> cross-sectional GaN nanowire lasers





Length: 430 – 450nm
Width: 100 – 150nm
Height: 4µm

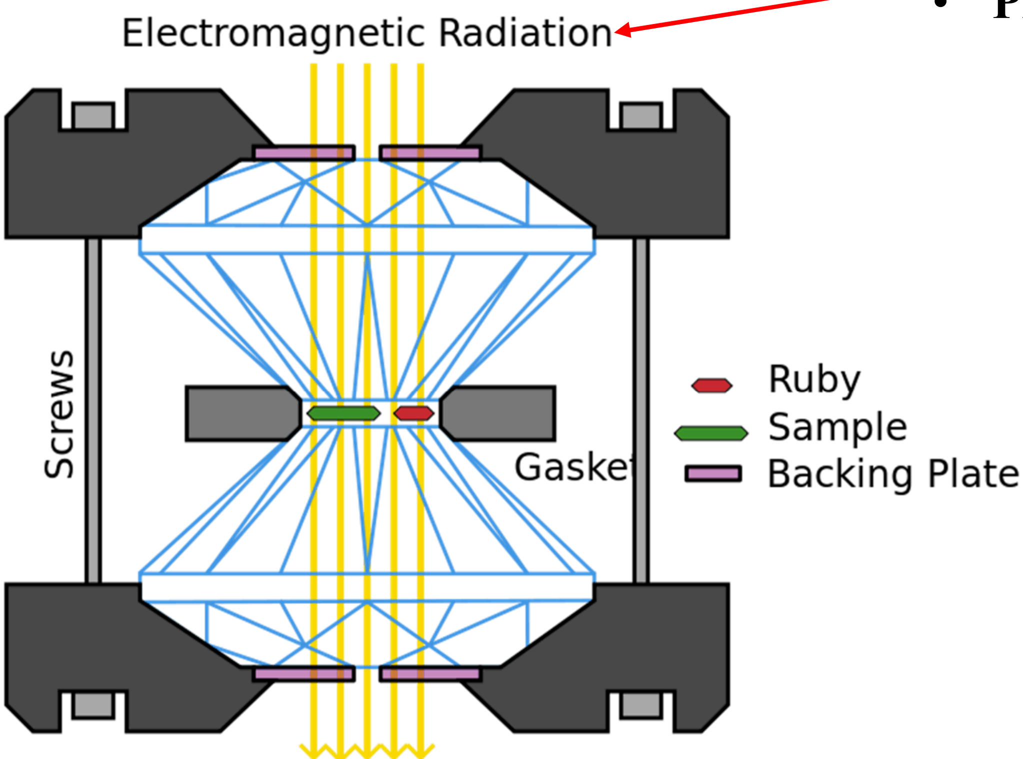
Polarization of lasing from rectangular cross-sectional nanowire lasers



Wire number	Extinction ratio
1	40:1
2	30:1
3	15:1
4	15:1

NW Lasing Under Presure

- X-ray diffraction
- PL excitation and collection

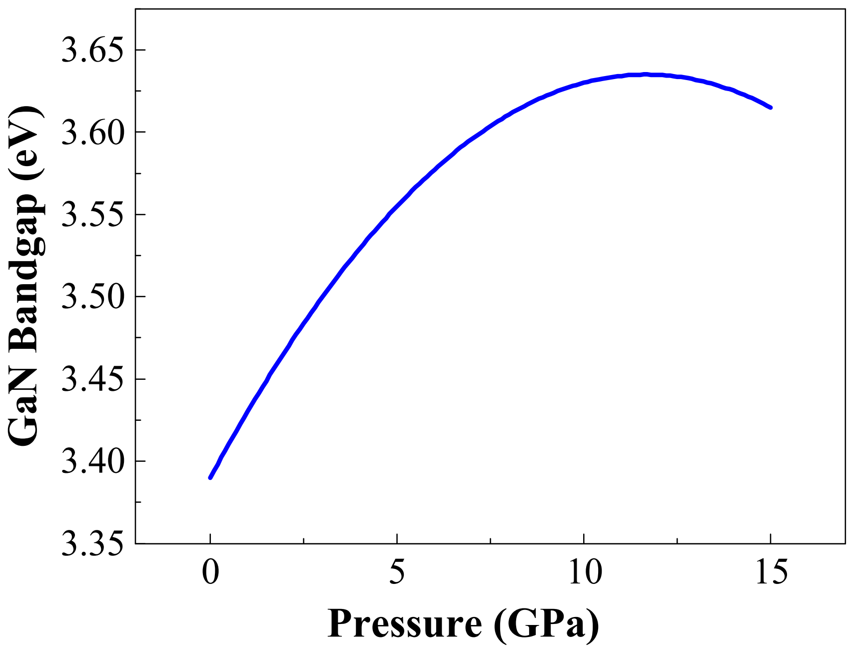


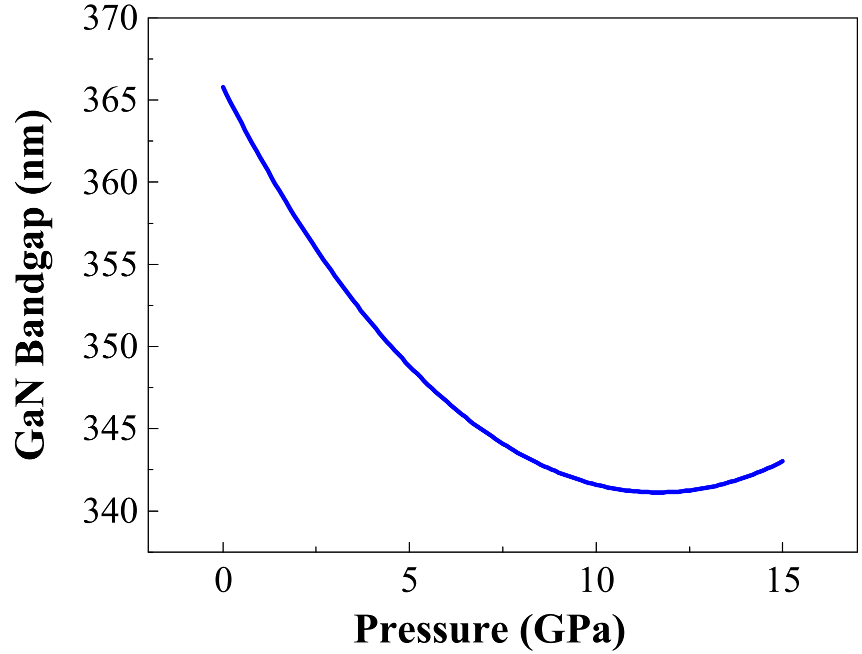
http://en.wikipedia.org/wiki/Diamond_anvil_cell

DAC: Diamond anvil cell

- **GaN nanowire lasers**
- **Pressure measured using typical Ruby signature photoluminescence line**
- **Hydrostatic pressure medium (silicone) transmits pressure isotropically**

GaN bandgap energy vs pressure





$E_g = E_g(0) + 4.2 \times 10^{-3}P - 1.8 \times 10^{-5}P^2$ (eV)
where P is pressure in kbar

Eg(0)=3.39ev=365nm

10 kilobars = 1 GPa

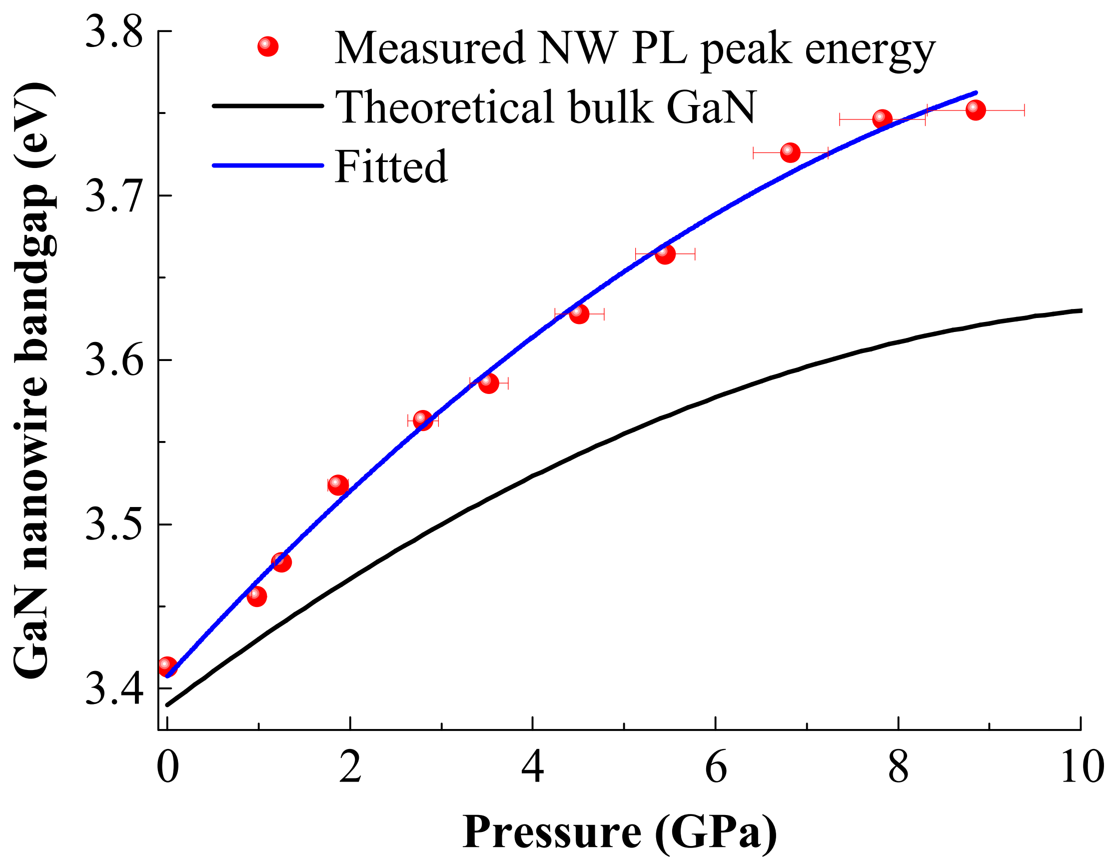
Pressure ↑

Bandgap energy ↑

Bandgap wavelength ↓

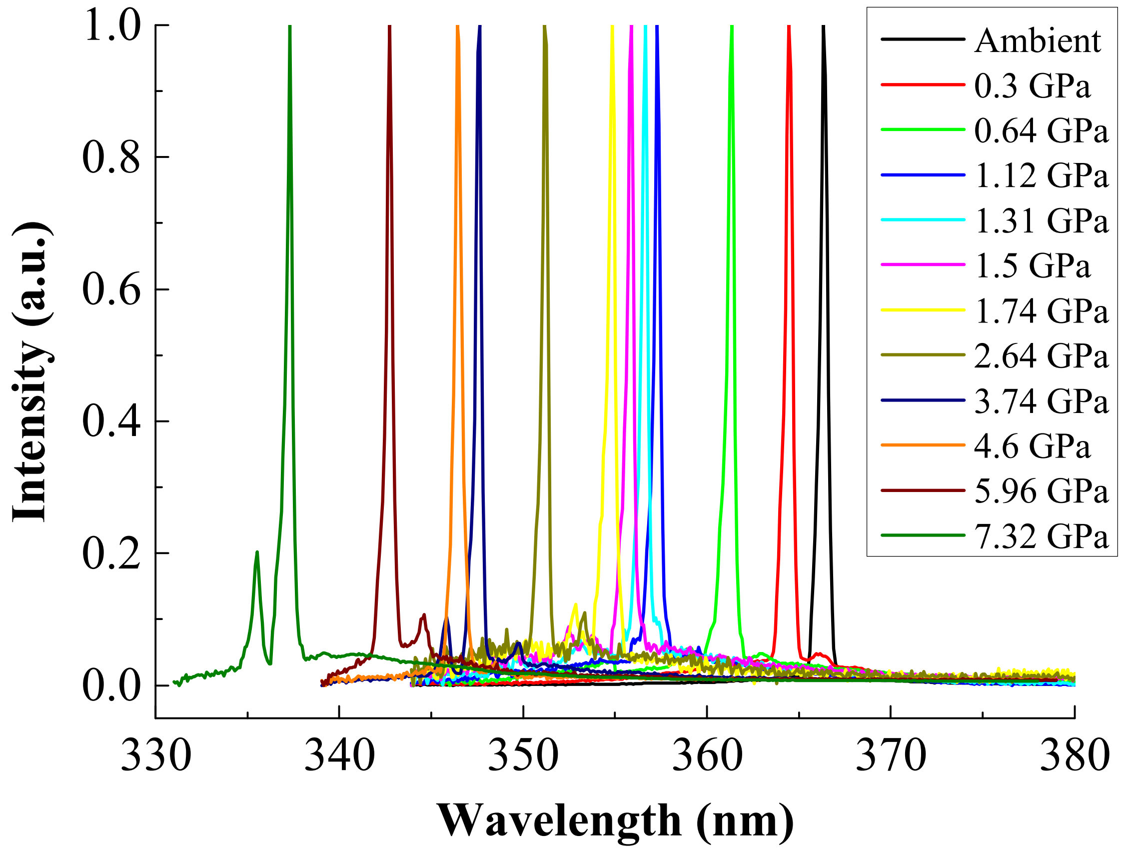
http://www.ioffe.rssi.ru/SVA/NSM/Semicond/GaN/bandstr.html#Dependence Pressure

Pressure coefficients of single GaN nanowire



- Larger pressure coefficients of GaN nanowires

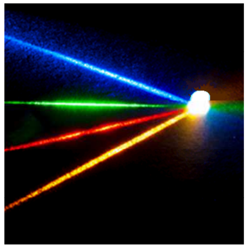
Lasing tuning of single GaN nanowire laser at different hydrostatic pressures

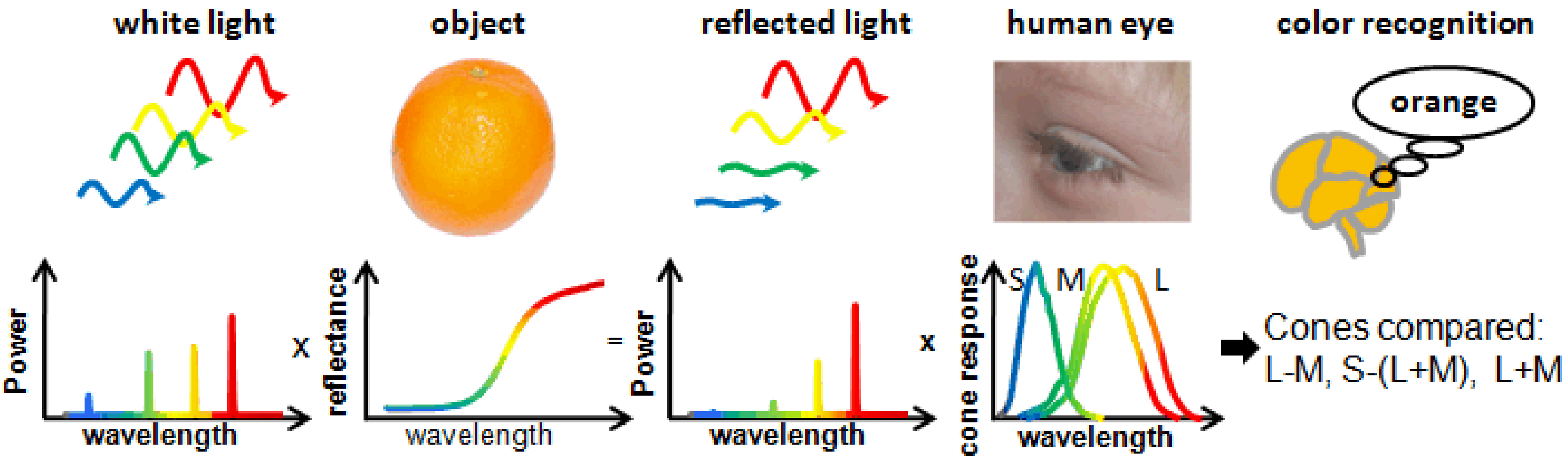


- **Continuous tuning**
- **~30nm lasing tuning**
- **Potentially >35nm lasing tuning**
- **Well defined fine tuning (<0.1nm)**
- **Multi-mode lasing as pump power increases**

Lasers for Solid State Lighting

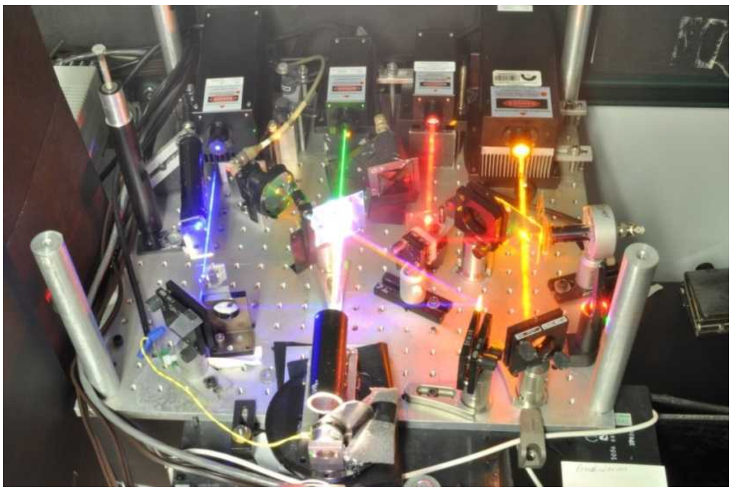
Could I use Lasers to Create White Light? (“Spikey” White Spectrum)

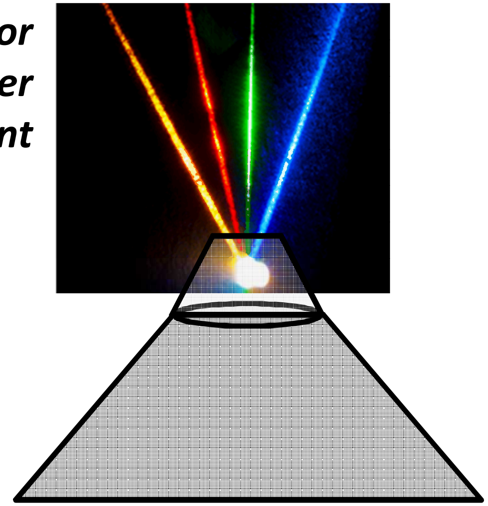




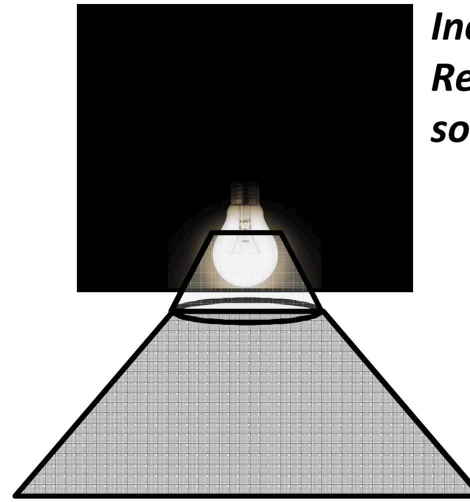
Spiky spectra have excellent color rendering: e.g., a 4-color laser illuminant

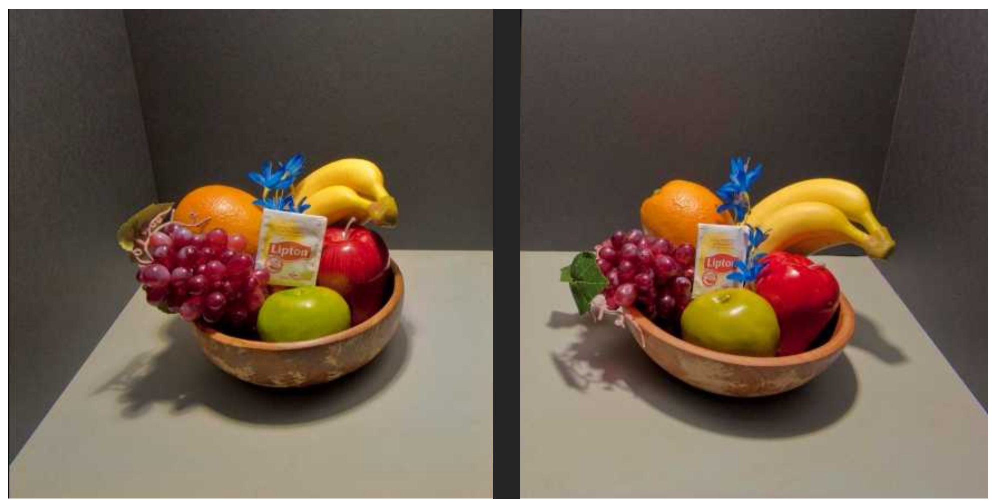
4-Color Laser Illuminant





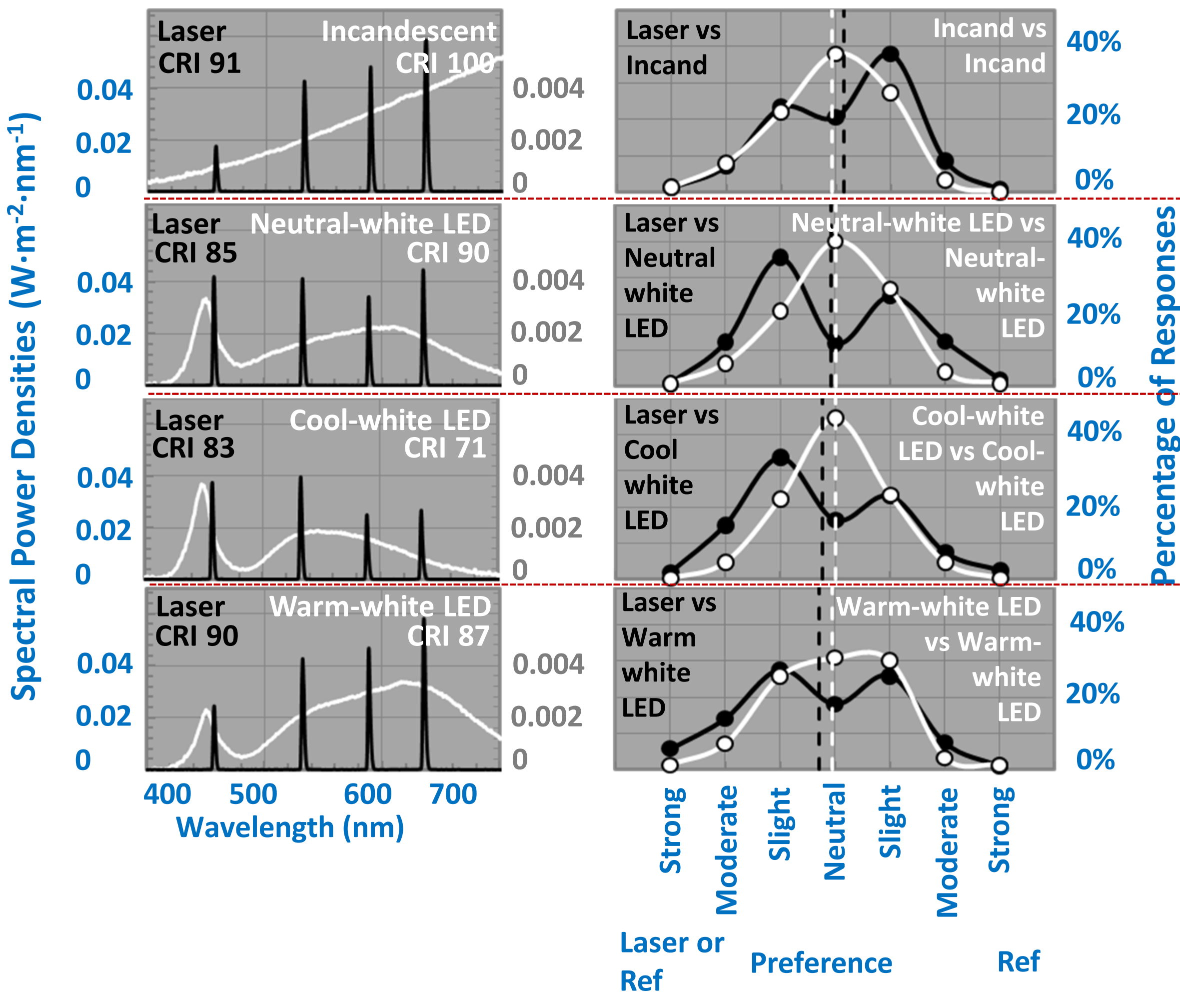
Incandescent Reference sources





A. Neumann, J.J. Wierer, Jr., W. Davis, Y. Ohno, S.R.J. Brueck, and J.Y. Tsao, "Four-color laser white illuminant demonstrating high color-rendering quality," Optics Express 19, A982-A990 (2011).

Result: RYGB laser and reference illuminants are nearly indistinguishable



Reference slightly preferred

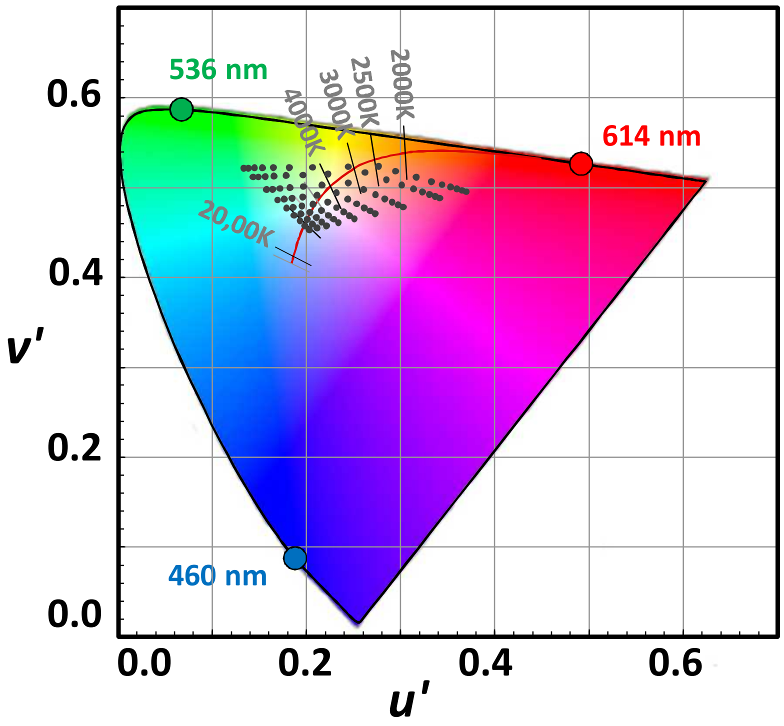
Lasers extremely slightly preferred

Lasers slightly preferred

Lasers slightly preferred

RYGB lasers:
the ultimate smart, ultra-efficient SSL source

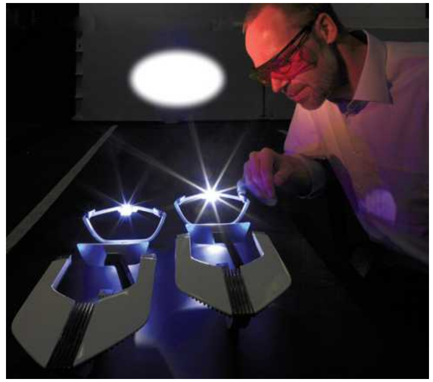
Wide color gamut



and easy integration with optics for directing light

Future of Lighting: Lasers for Illumination…

Headlights, BMW



Movies

Laser Projector

Future of Lighting: "Smart" Lighting

"2nd Wave Lighting: Smart and Feature Rich

Courtesy of E.F. Schubert

Integrated Illumination and Displays

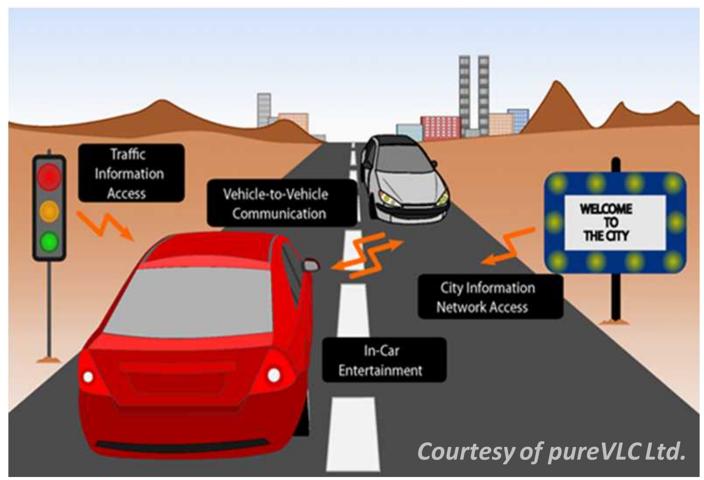
Courtesy of NEONNY Technologies

Human Health, Well Being and Productivity

Courtesy of Dan Picasso and the Wall Street Journal

Courtesy of SOA architects

Agriculture



Courtesy of pureVLC Ltd.

Communication

Courtesy of Shuntaro Yamazaki, AIST

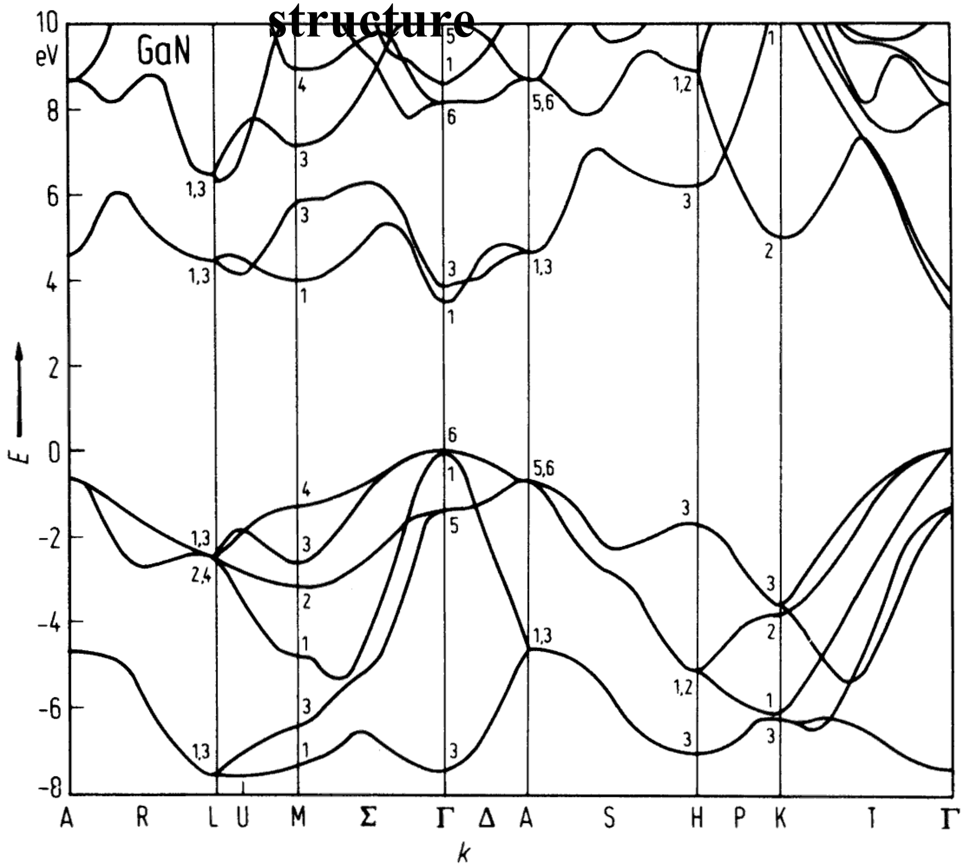
Light-Field Mapping

M.H. Crawford, J.J. Wierer, A.J. Fischer, G.T. Wang, D.D. Koleske, G.S. Subramania, M.E. Coltrin, J.Y. Tsao, R.F. Karlicek, Jr., "Solid-State Lighting: Toward Smart and Ultra-Efficient Materials, Devices, Lamps and Systems," in D.L. Andrews, Ed., "Photonics Volume 3: Photonics Technology and Instrumentation" (Wiley, 2014).

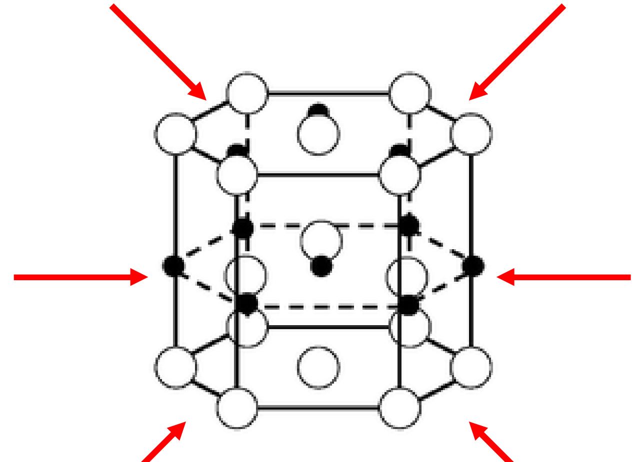
END

Crystal structure transition of GaN

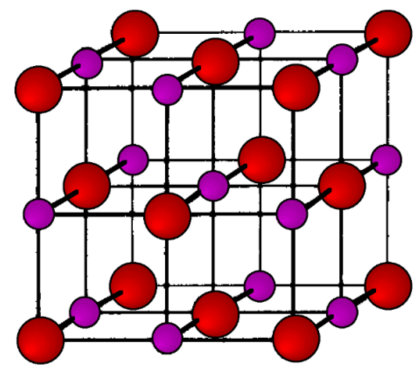
GaN band structure



http://www.ioffe.ru/SVA/NSM/Semicond/GaN/bandstr.html



Wurtzite: direct bandgap



Rock salt: indirect bandgap

Good news:

Transition of GaN wurtzite → rock salt doesn't occur until >40 GPa

Slide 57

IB1 doesn't it make more sense to show slides 5&6 after 9?a

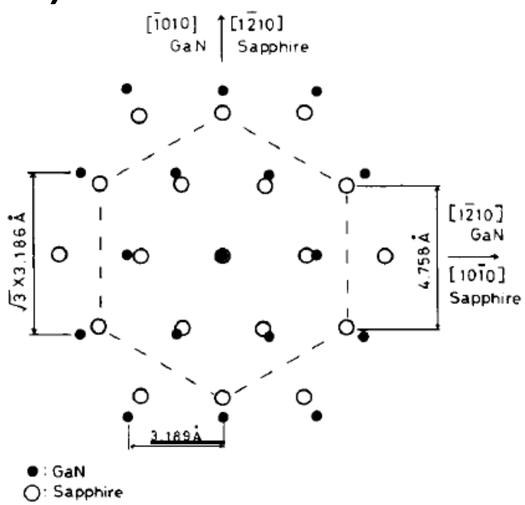
Brener, Igal, 6/19/2014

III-nitride breakthroughs

Renewed interest in late 1980's, but there were three problems to be solved.

1. No GaN substrates.

- **Need to learn how to grow on lattice mismatched substrates.**
- **Akasaki and H. Amano demonstrated buffer layer growth on sapphire producing lower defect density layers of GaN. (1986)**



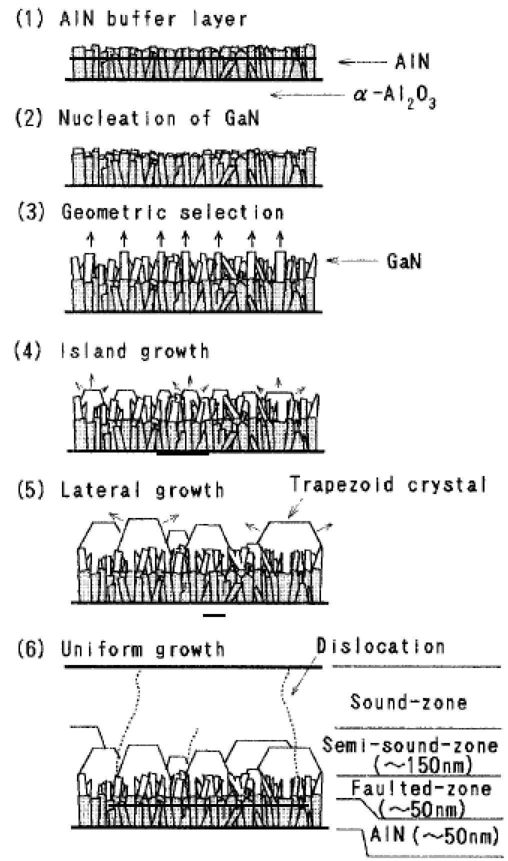


Fig. 6. Schematic diagrams showing the growth process of GaN on the AlN buffer layer as the cross sectional views.

I. Akasaki, H. Amano, et al. J. Crys. Growth, 98, 209, 1989.

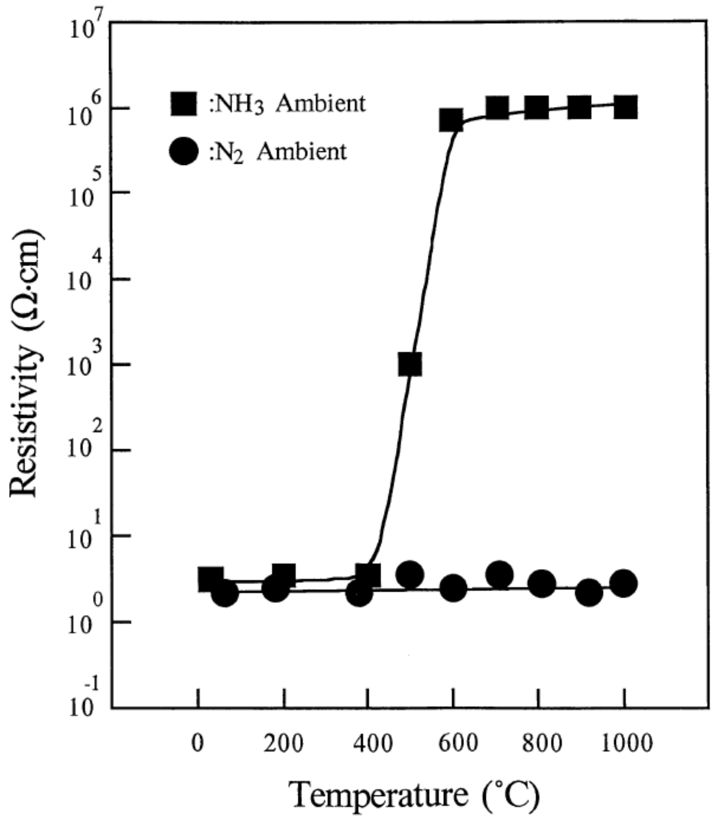
Courtesy: J. Wierer, J. Tsao

III-nitride breakthroughs

Renewed interest in late 1980's. But there were three problems to be solved.

2. No p-type doping.

- **Mg doped GaN was not producing p-type conductivity. Why?**
- **Amano (1989) showed electron beam irradiation creates active Mg.**
- **Nakamura (1992) demonstrated that Hydrogen passivates Mg acceptors**



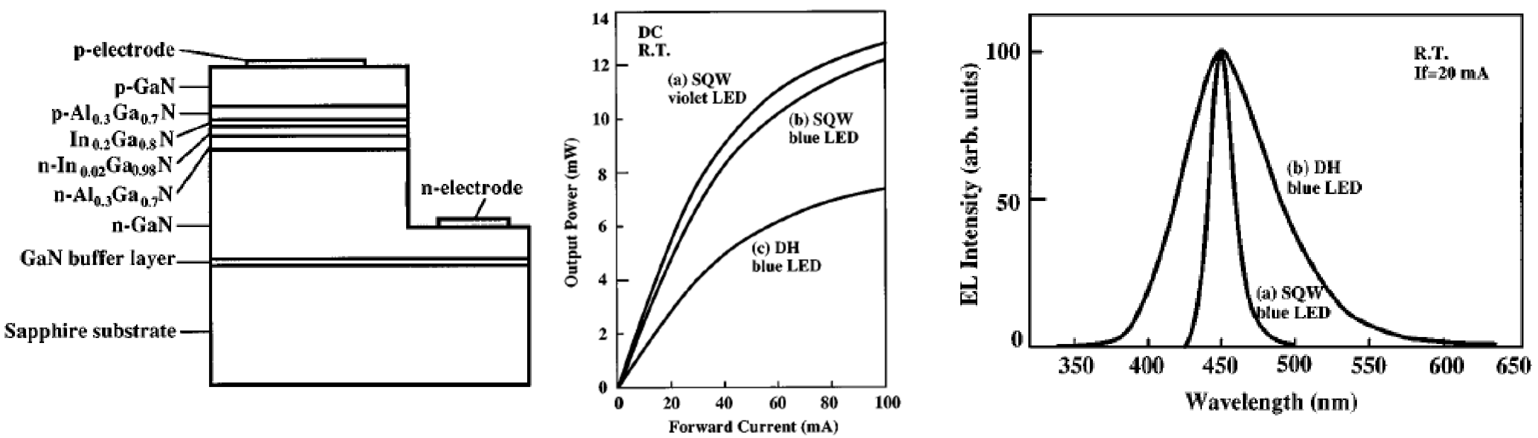
Courtesy: J. Wierer, J. Tsao

III-nitride breakthroughs

Renewed interest in late 1980's. But there were three problems to be solved.

3. GaN emission is in the near-UV, not the visible.

- **Need to learn how to grow lower energy InGaN material.**
- **Nakamura (1995) demonstrated blue LEDs with ~10% quantum efficiency.**

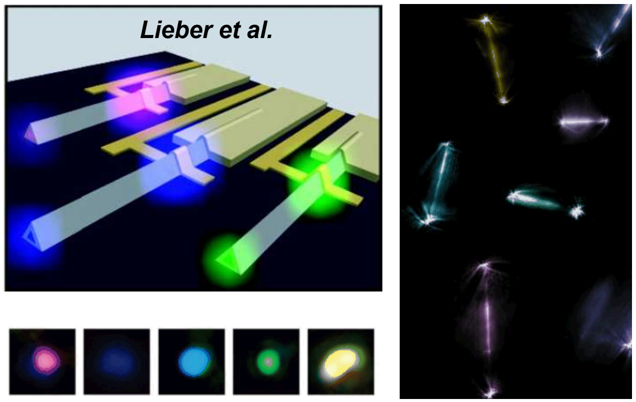


S. Nakamura, et al. ALP, 64, 1868, 1995.

Courtesy: J. Wierer, J. Tsao

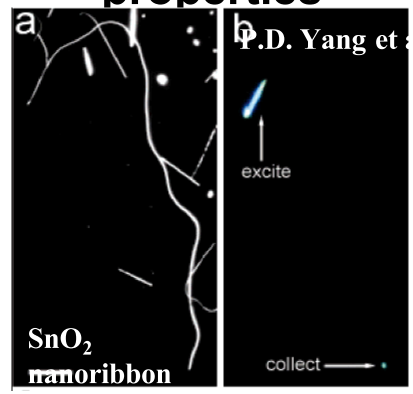
Semiconductor Nanowires (NWs)

Reduced dimensionality, high crystalline quality, high atomic surface/bulk ratio, size (intersects physical characteristic length scales) can lead to enhanced & novel properties



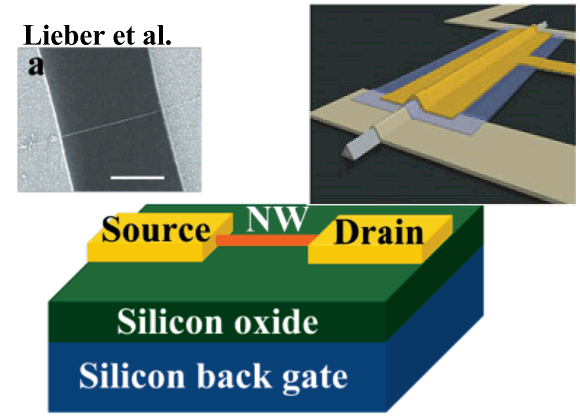
LEDs and lasers

- Nanosized light sources
- Higher efficiency due to lack of defects
- High light extraction



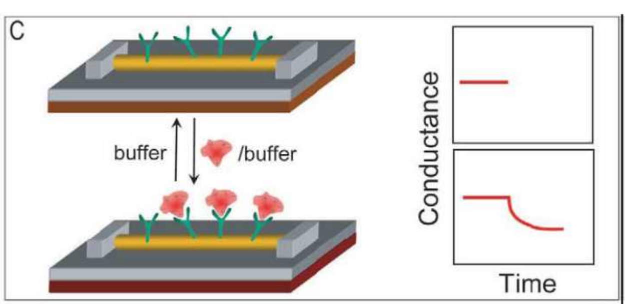
Waveguides and Filters

- coupled with nanowire light sources, building blocks for nanophotonics circuitry



Transistors/HEMTs

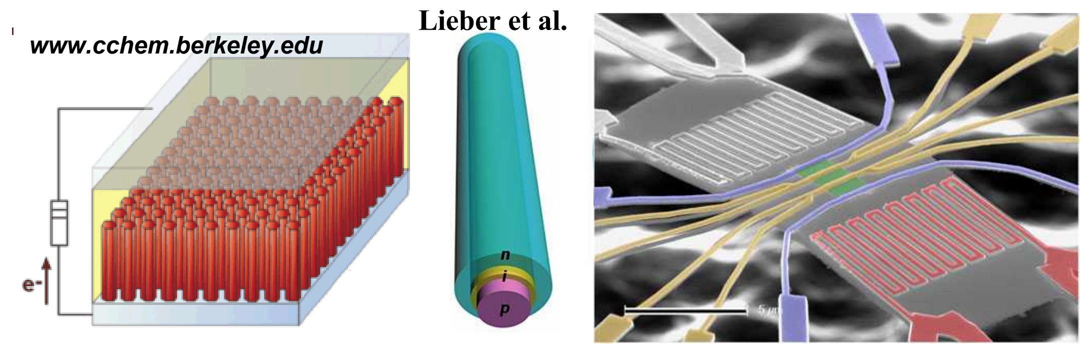
- improved performance characteristics
- small size



Lieber et al.

Chem/bio-sensors

- large atomic surface/bulk ratio leads nanowire depletion & ultrahigh sensitivity



Heath et al.

Energy Harvesting

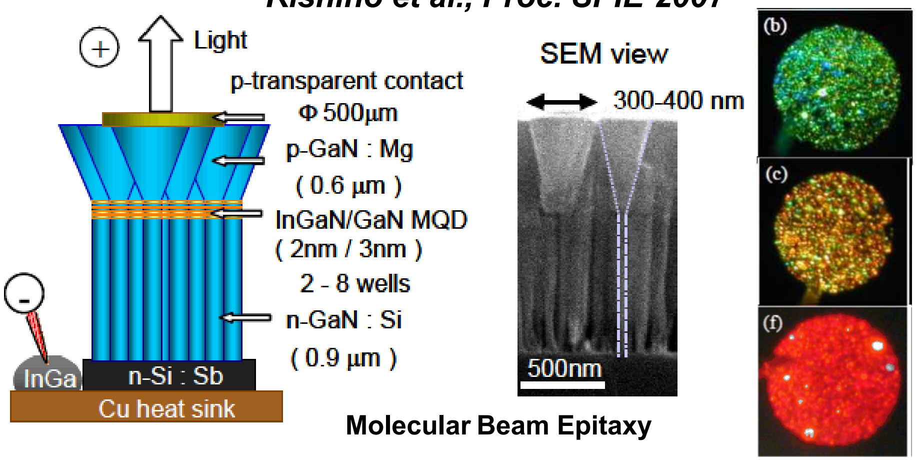
- Nanowire Photovoltaics
- Thermoelectrics
- Piezoelectric energy generation

Nanostructured InGaN LEDs

Axial LED Geometries

Self-assembled Nanorods, p- GaN Planarization

Kishino et al., Proc. SPIE 2007



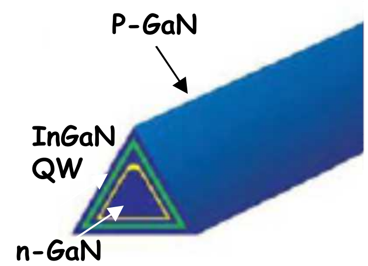
→Indium composition variations between nanorods; leads to broad spectra

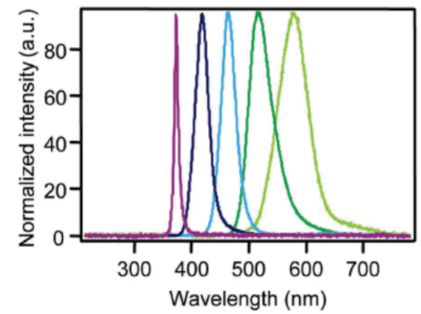
Also, Spin-on-glass planarization *Kim et al., Nanolett. 2004*

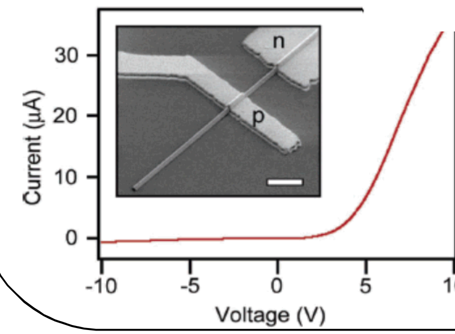
Radial (Core-Shell) LED Geometries

n-GaN/InGaN/p-GaN core/shell Nanowires

Qian et al., Nat Mat. 2005





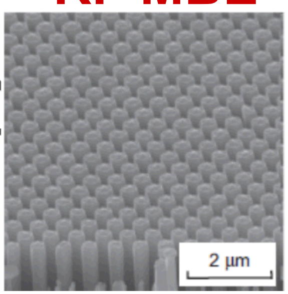


Single NW:
EQE= 3.9%
@ 540 nm

Outstanding Issues:

- NW uniformity for InGaN composition and color con…
  - → Selective area growth
- Device architectures

RF MBE

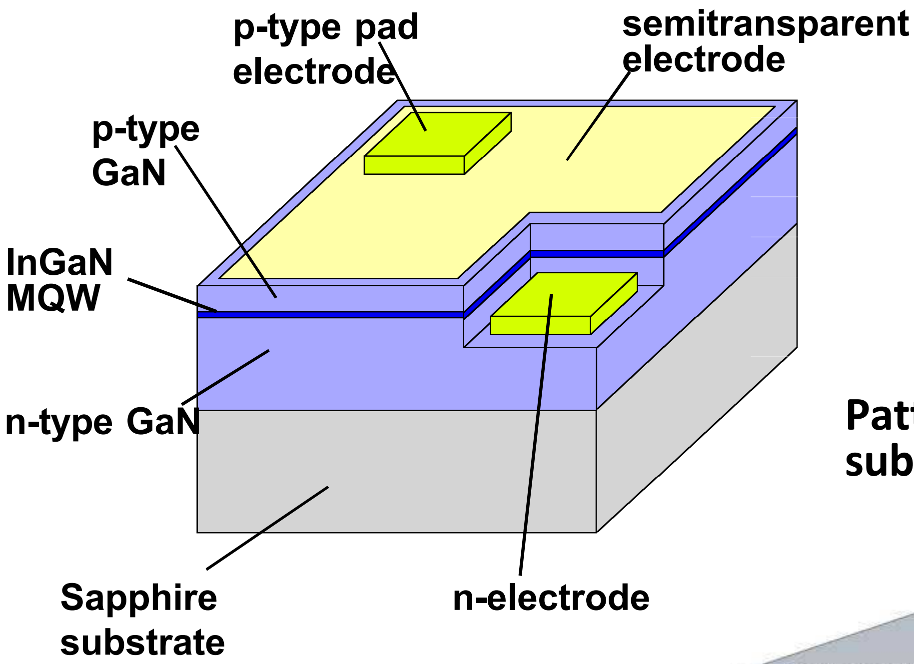


Kishino et al., JCG 2009

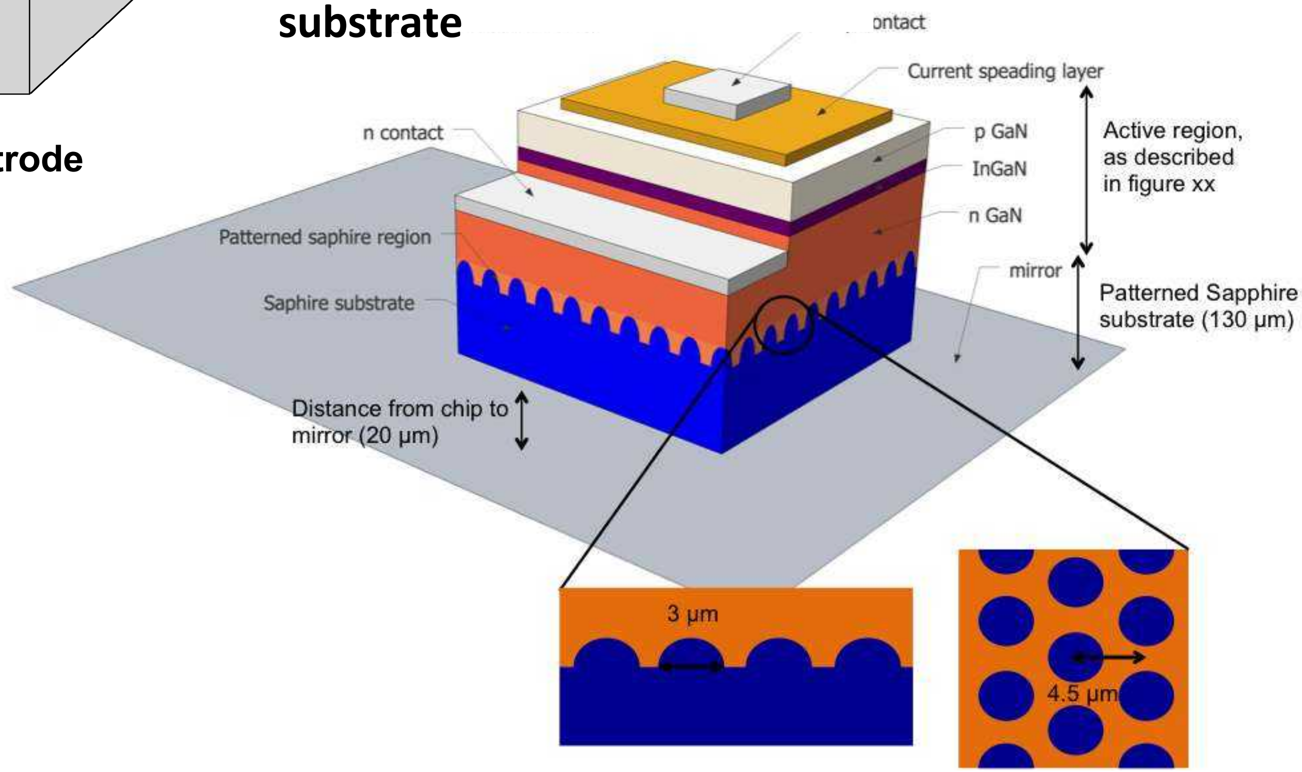
MOCVD

Hersee et al., Electron. Lett. 2009

Typical Blue LED Structure on Sapphire



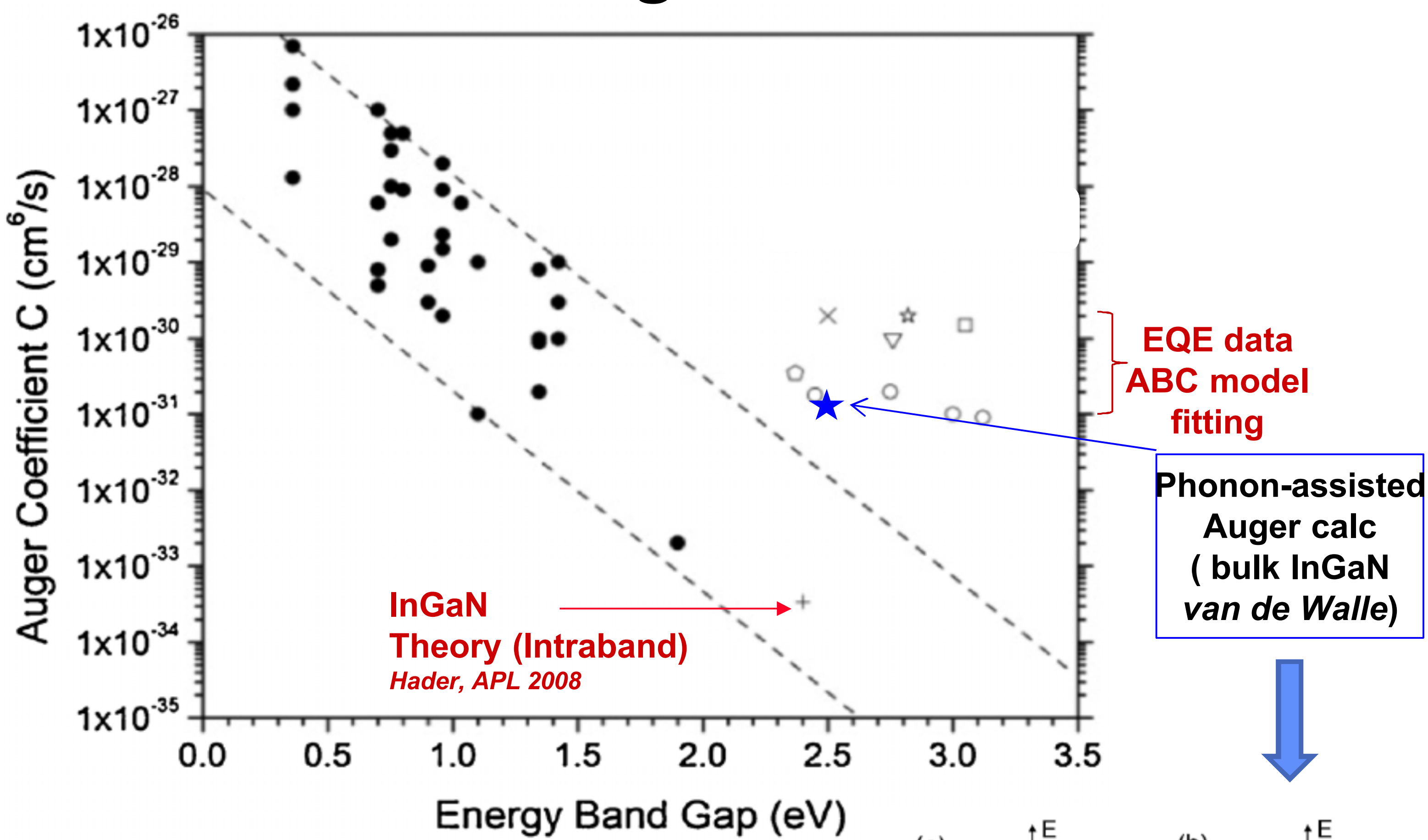
Patterned sapphire substrate

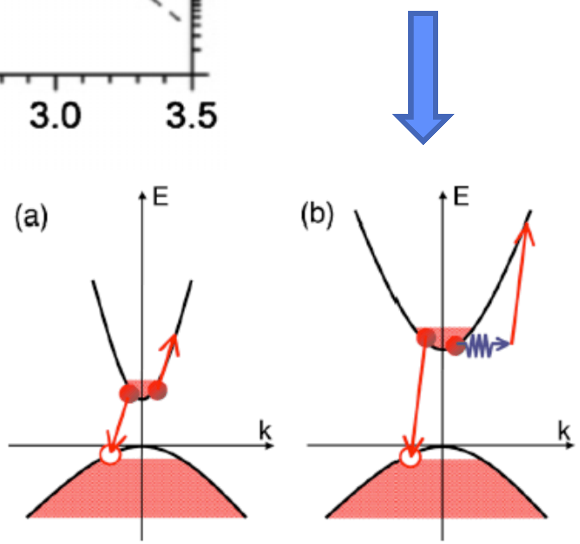


Weisbuch)

Auger

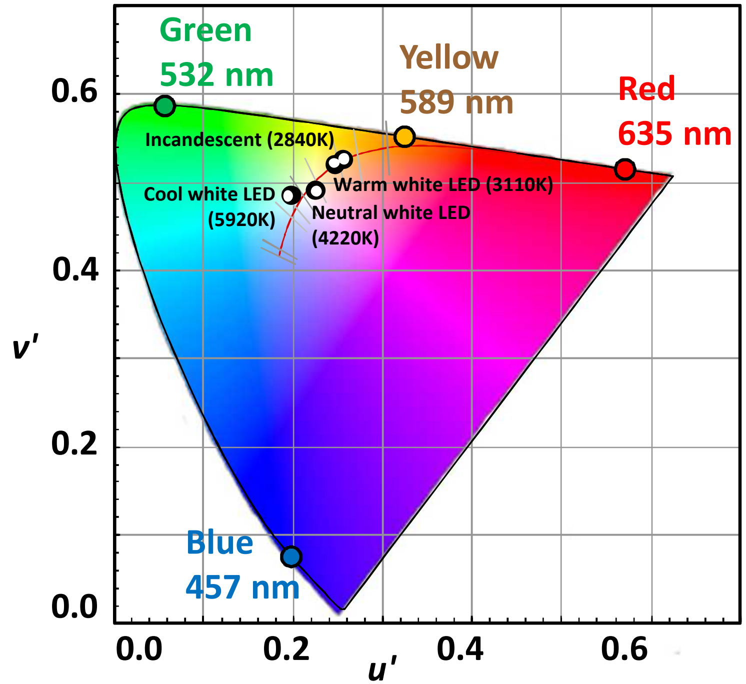
Piprek, PSSA, 2010





- recent paper: Auger creates high energy carriers which contribute to leakage (diplomatic solution)

Light "Temperature", Chromaticity, etc



From indicators to illuminators

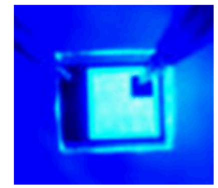
5mm LED:

~0.2 mm x 0.2 mm die area.

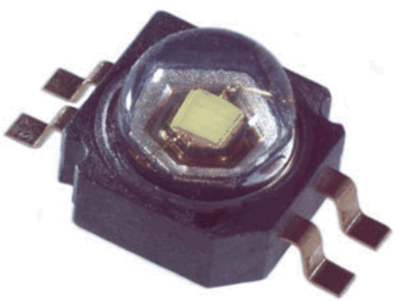
20mA max operating current.

Epoxy encapsulation.

10's of mW of optical power.



~2000



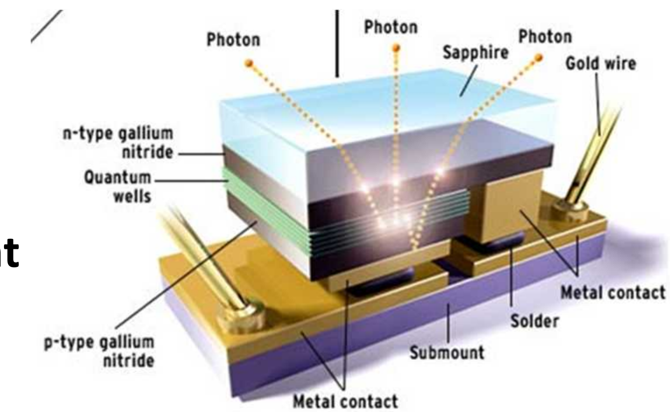
High power LED:

~1mm x 1mm die area

700mA-1A max operating current

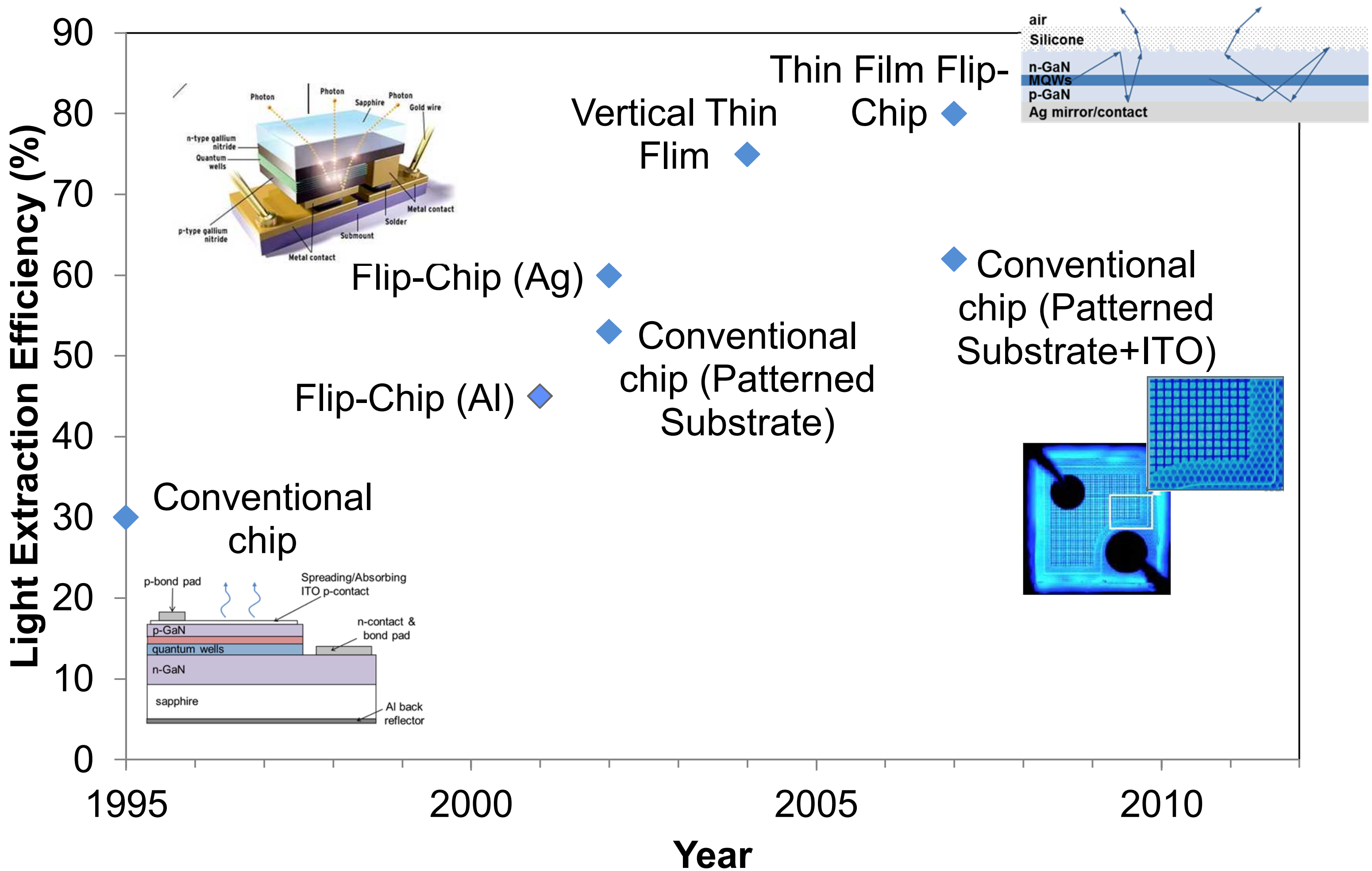
silicone encapsulation

~1's of W of optical power.



Courtesy: J. Wierer, J. Tsao

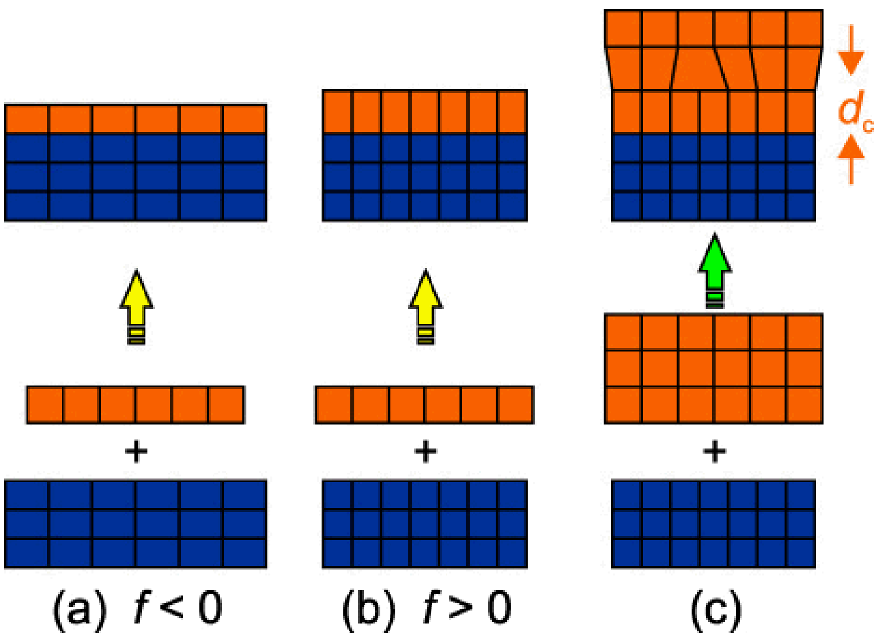
LED Extraction Efficiency Over Time



Courtesy: J. Wierer, J. Tsao

A Closer Look at III-Nitride Semiconductors: Defects!

What happens when 2 crystals don't have the same lattice constant and we try to grow one on top of the other



(iopscience.org)

Electron Micrograph (cross section)