Innovations in Solid State Lighting

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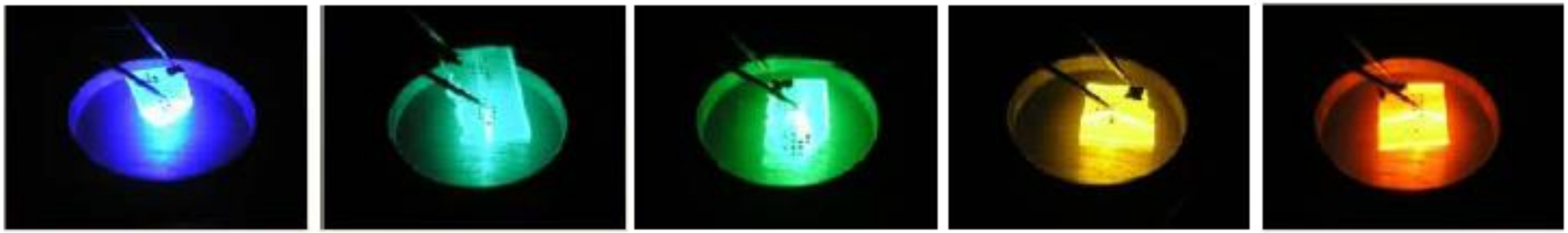


Outline

1. **Introduction**
   - History
   - Is sun light the best for humans and plants?
2. **LED Lighting**
   - Tunnel-Junction (TJ) blue/green LEDs with EQE over 70%/50%
   - Micro LED, green LED for red LED
3. **Laser Lighting**
   - High Power Semipolar LDs
   - Li-FI with LEDs and LDs

Introduction

GaN/InGaN on Sapphire Research

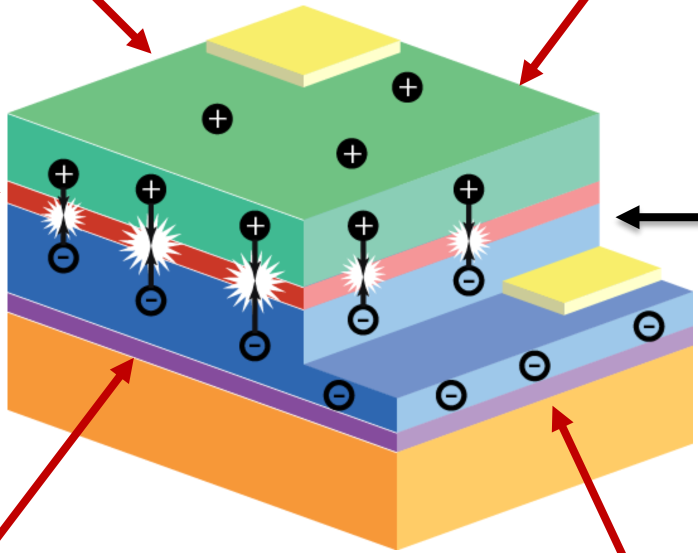
	Year	Researcher(s)	Achievement
GaN	1969	Maruska & Tietjen	GaN epitaxial layer by HVPE
	1973	Maruska *et al.*	1st blue Mg-doped GaN MIS LED
	1983	Yoshida *et al.*	High quality GaN using AlN buffer by MBE
	1985	Akasaki & Amano *et al.*	**High quality GaN using AlN buffer by MOCVD**
	1989	Akasaki & Amano *et al.*	**p-type GaN using LEEBI** (p is too low to fabricate devices)
	1991	Nakamura	**Invention of Two-Flow MOCVD**
	1991	Moustakas	High quality GaN using GaN buffer by MBE
	1991	Nakamura	**High quality GaN using GaN buffer by MOCVD**
	1992	Nakamura *et al.*	**p-type GaN using thermal annealing,** **Discovery hydrogen passivation** (p is high enough for devices)
InGaN	1992	Nakamura *et al.*	**InGaN layers with RT Band to Band emission**
	1994	Nakamura *et al.*	**InGaN Double Heterostructure (DH) Bright Blue LED (1 Candela)**
	1995	Nakamura *et al.*	**InGaN DH Bright Green LED**
	1996	Nakamura *et al.*	**1st Pulsed Violet InGaN DH MQW LDs**
	1996	Nakamura *et al.*	1st CW Violet InGaN DH MQW LDs
	1996	Nichia Corp.	Commercialization **White LED using InGaN DH blue LED**

Contributions towards efficient blue LED

***p*-type GaN activated by thermal annealing** by *Nakamura et al.*, **1992**

Hydrogen passivation was clarified as an origin of hole compensation

***p*-type GaN activated by Electron Beam Irradiation** by *Akasaki & Amano*, **1989**



InGaN Emitting (Active) Layer by *Nakamura & Mukai*, **1992**

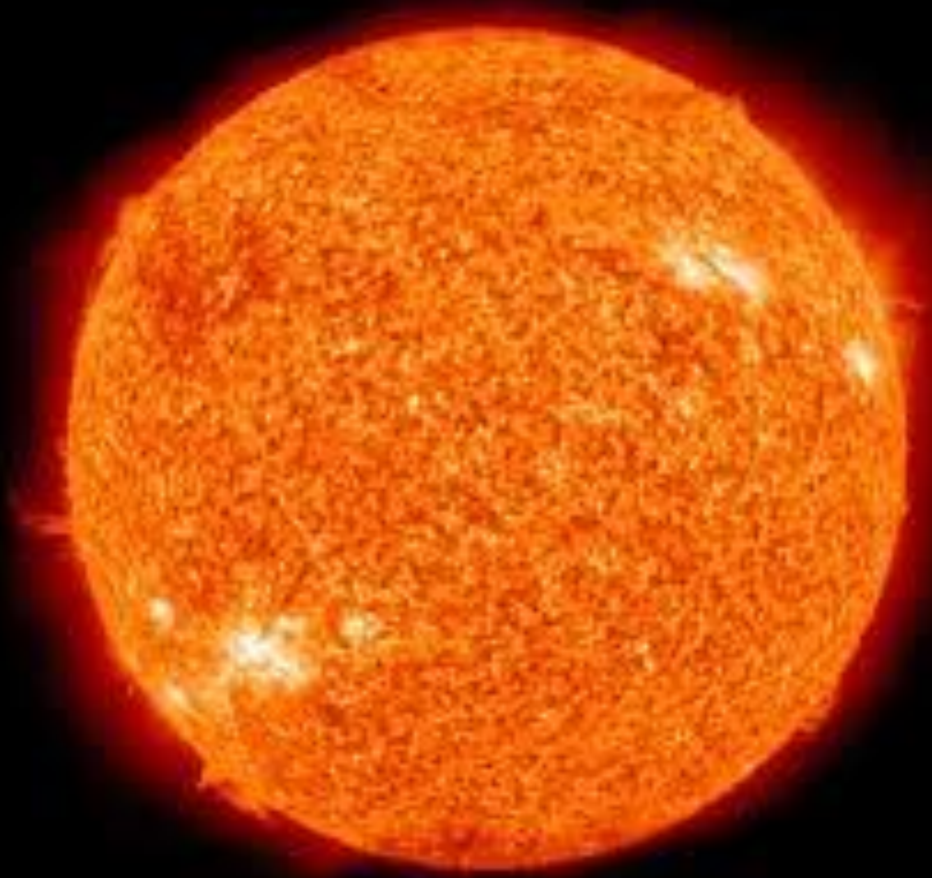
n-type GaN

Sapphire substrate

GaN Buffer by *Nakamura*, **1991**

AlN Buffer by *Akasaki & Amano*, **1985**

First Source of Light for Life: Our Sun



Conventional White LED (Blue LED + Phosphor)

Strong Blue LED light disrupts the circadian cycle or suppresses melatonin?

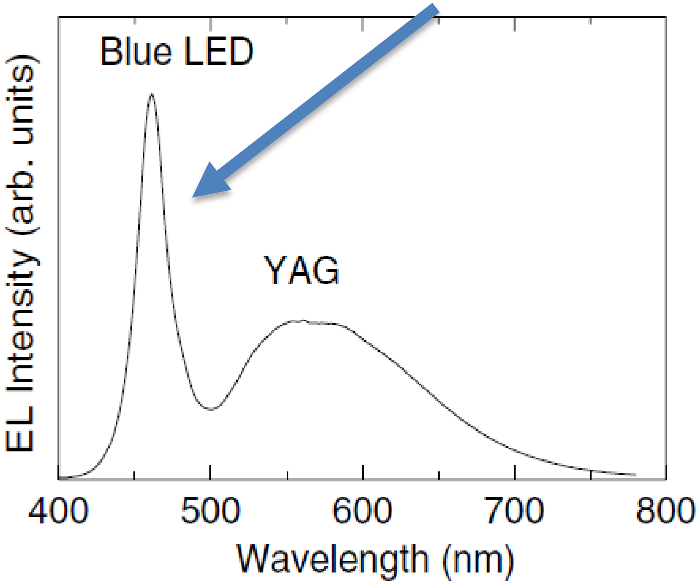


Figure 2. The typical emission spectrum of a white LED using a YAG phosphor at 20 mA. T_{cp} is 6500 K.

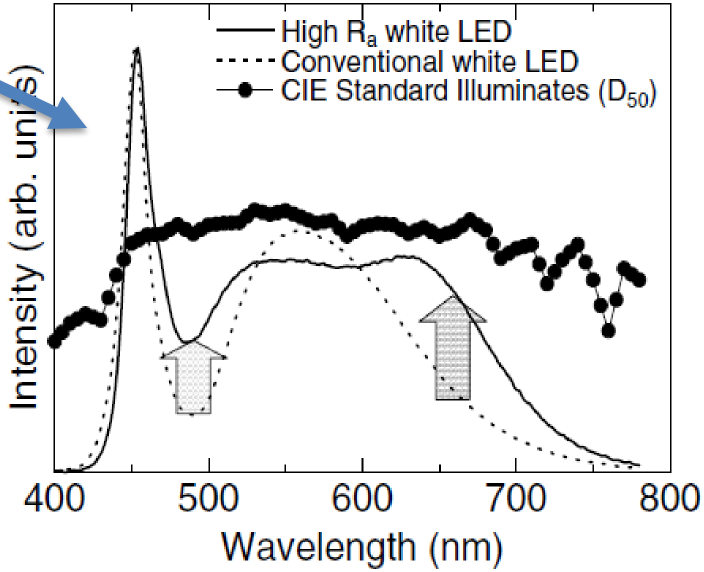


Figure 3. The spectra of the ultra-high R_a white LED, the conventional white LED and CIE Standard Illuminates (D_{50}). All of T_{cp} are 5000 K.

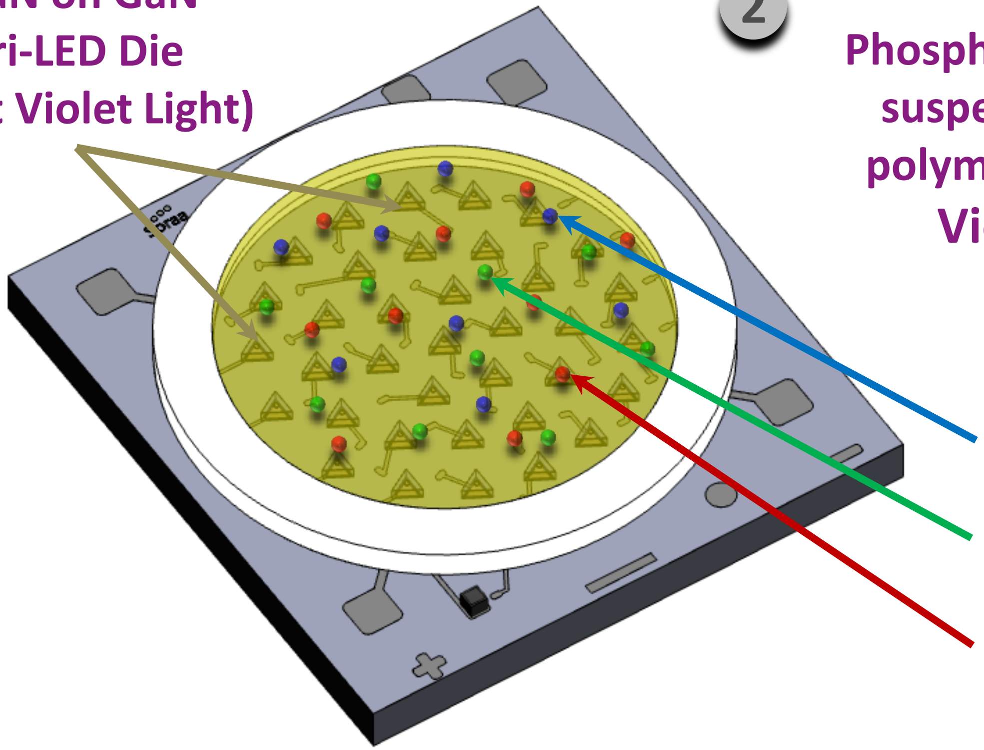
Narukawa et al., J. Phys. D: Appl. Phys. 43 (2010) 354002

Plant Factory using Blue/Red LEDs in Clean Room

Growth rate is 2.5 times (the latest: 5 times) higher.
Yield from the plants is 50% to 90%
Water usage is only 1% compared with in the field

What's VP$_3$?

VP$_3$ = Violet and 3 Phosphor



1

GaN on GaN
Tri-LED Die
(Emit Violet Light)

2

Phosphor Particles suspended in a polymer convert Violet to

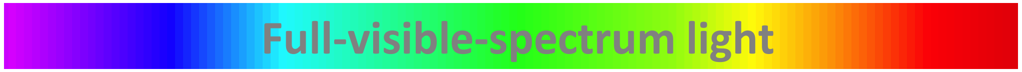
Blue

Green

Red

3

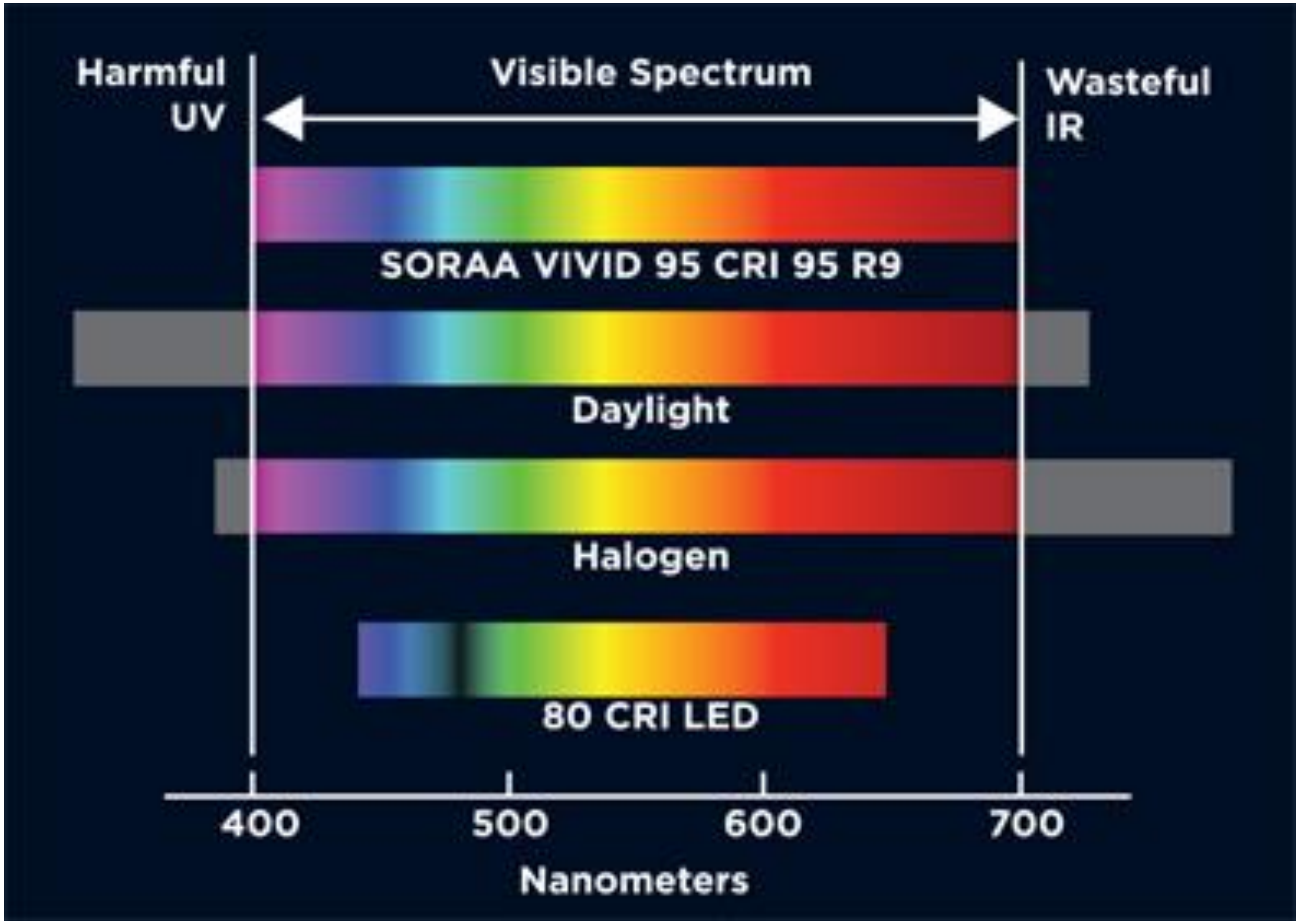
Resulting in



Full-visible-spectrum light

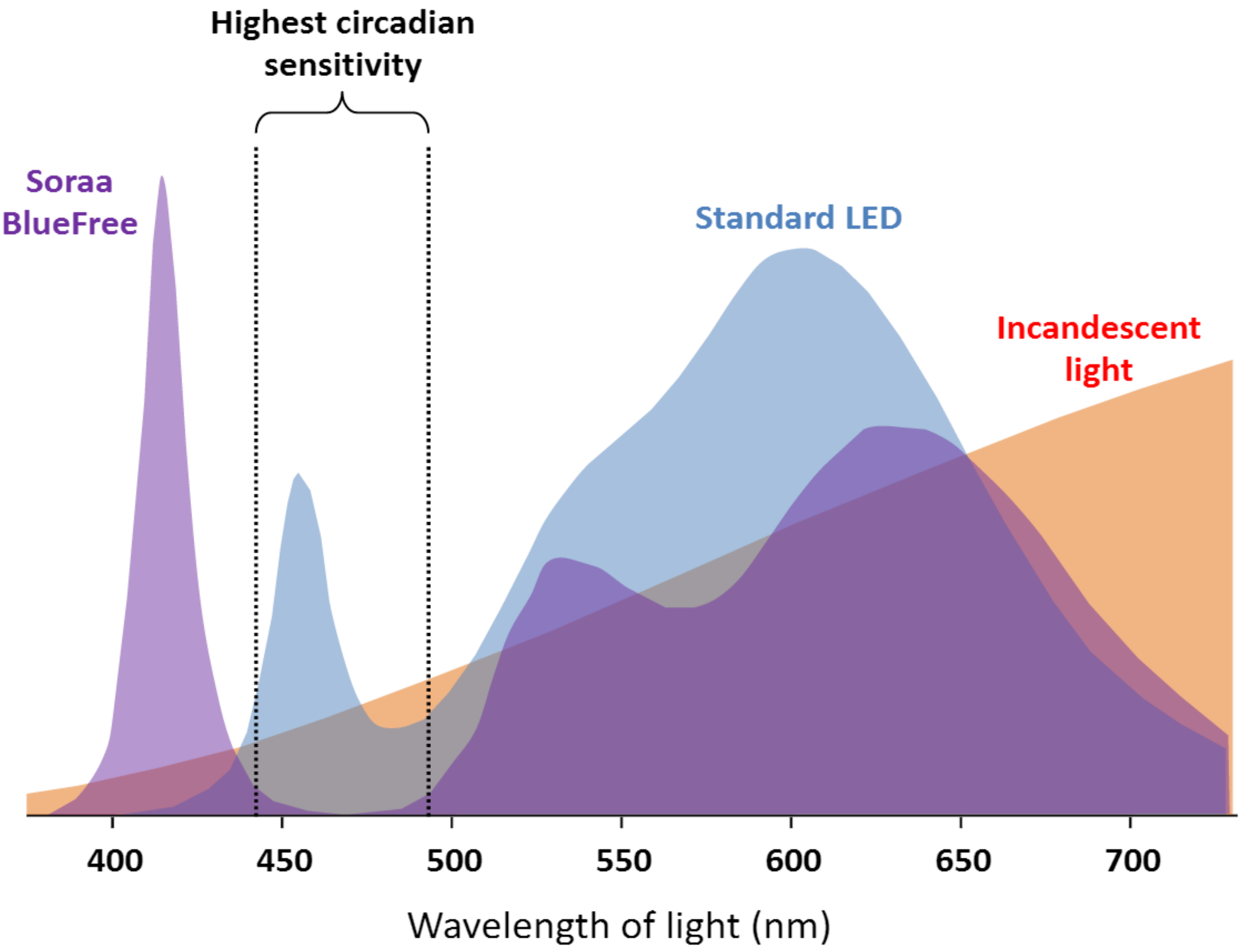
What’s VP_3?

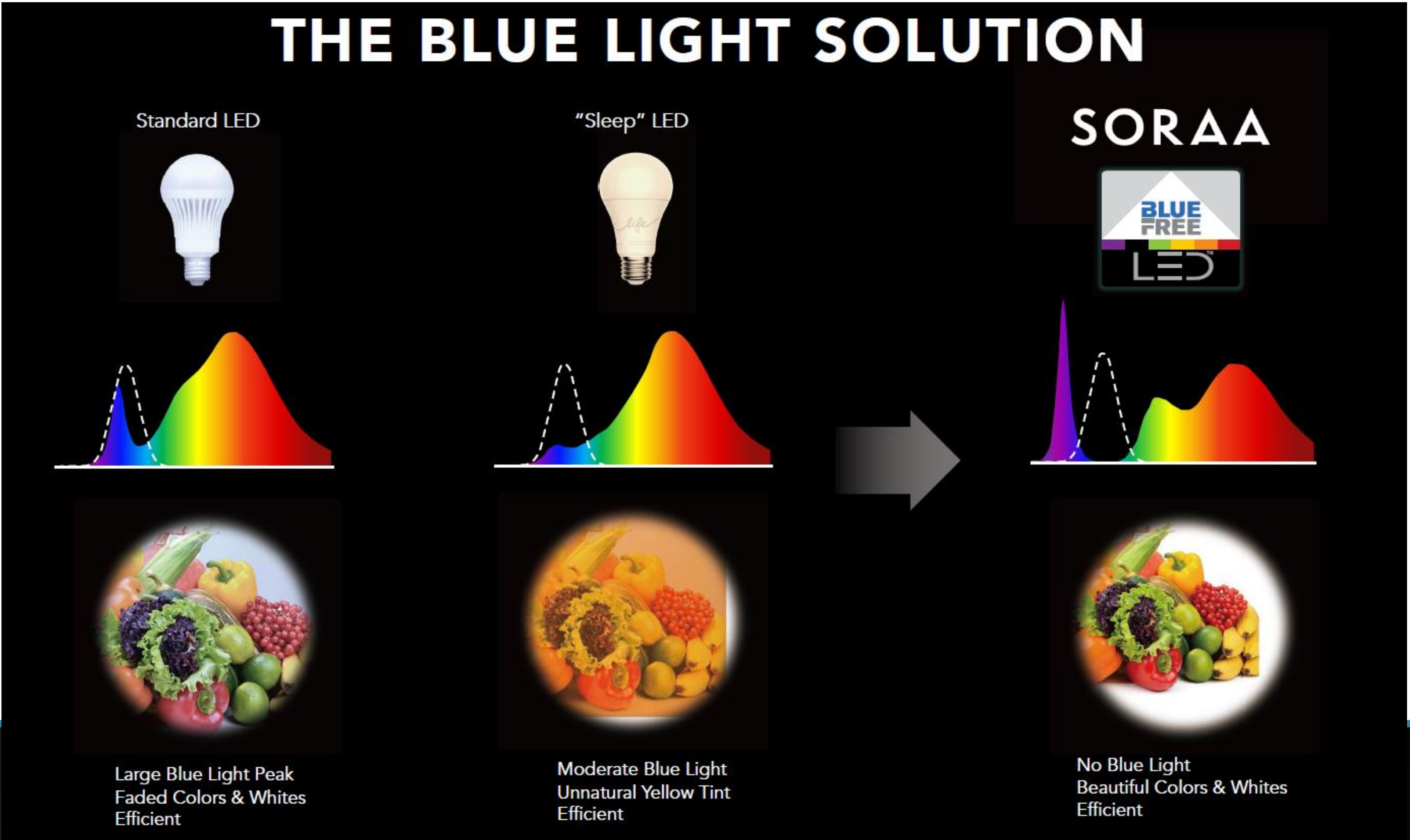
VP_3 = Violet and 3 Phosphor



Soraa's New Helia Bulb Lamp

http://www.digitaltrends.com/home/soraa-helia/#/7





THE BLUE LIGHT SOLUTION

Standard LED

Large Blue Light Peak
Faded Colors & Whites
Efficient

"Sleep" LED

Moderate Blue Light
Unnatural Yellow Tint
Efficient

SORAA

BLUE FREE LED™

No Blue Light
Beautiful Colors & Whites
Efficient

Soraa's New Helia Bulb Lamp

http://www.digitaltrends.com/home/soraa-helia/#/7

2017 CES Innovation award(January 4, 2017)

Using Soraa's BlueFree LEDs, David says the Helia emits almost zero blue light while still retaining a "soft white color." The bulb adapts to your home's sunrise and sunset times as well as your habits to trigger the night mode. Helia also provides "plenty of blue light" in the morning to wake you up.

Read more: http://www.digitaltrends.com/home/soraa-helia/#ixzz4UvVGdiro

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PP. 276 Nature, Vol. 519, 19 March 2015

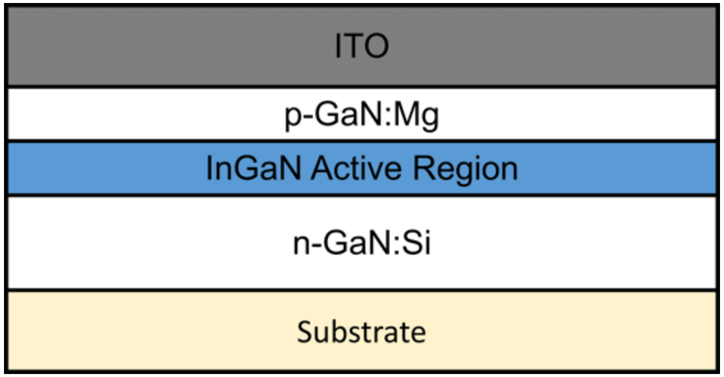
IMAGINECHINA/CORBIS

THE MYOPIA BOOM

LED Lighting: Tunnel Junction Devices

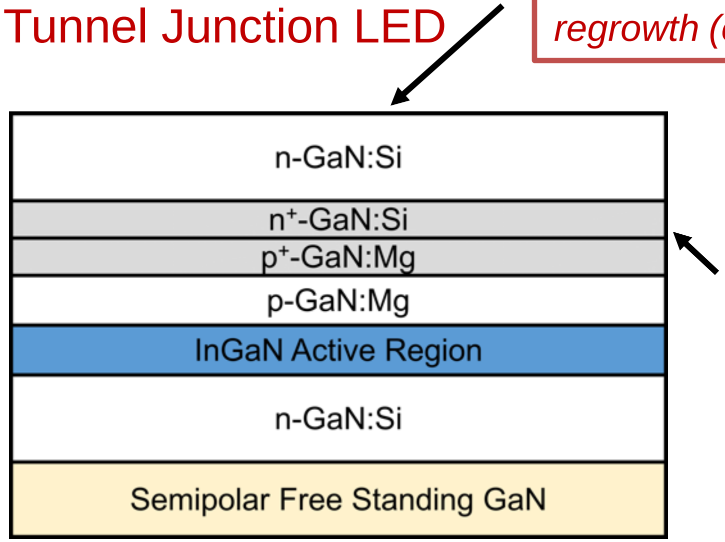
GaN Tunnel Junction Advantages

Transparent Conducting Oxide LED



Tunnel Junction LED

By Professor Jim Speck Use of MBE for N-GaN regrowth (eliminate H)

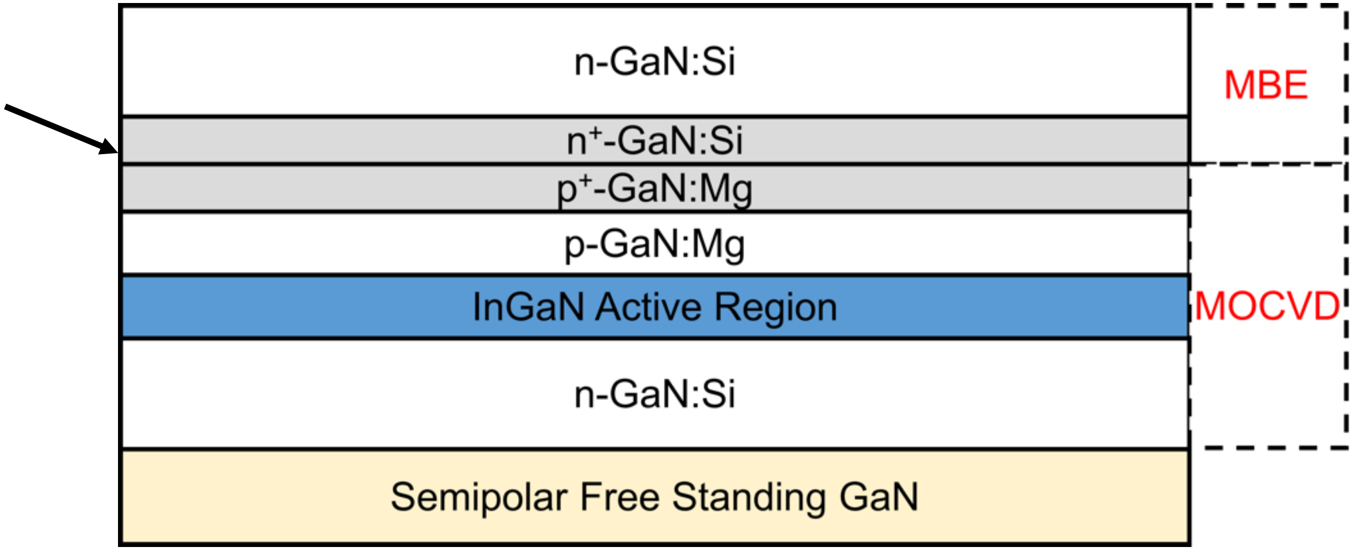


Tunnel junction eliminates need for standard p-contacts

- Increased Internal Quantum Efficiency (IQE) for LEDs
- Could lower voltage in edge emitting laser diodes
- Reduction in optical loss and increase of design space for GaN VCSELs
- Increase in process design space due to buried p-GaN

Tunnel Junction LEDs

Tunnel junction at regrowth interface

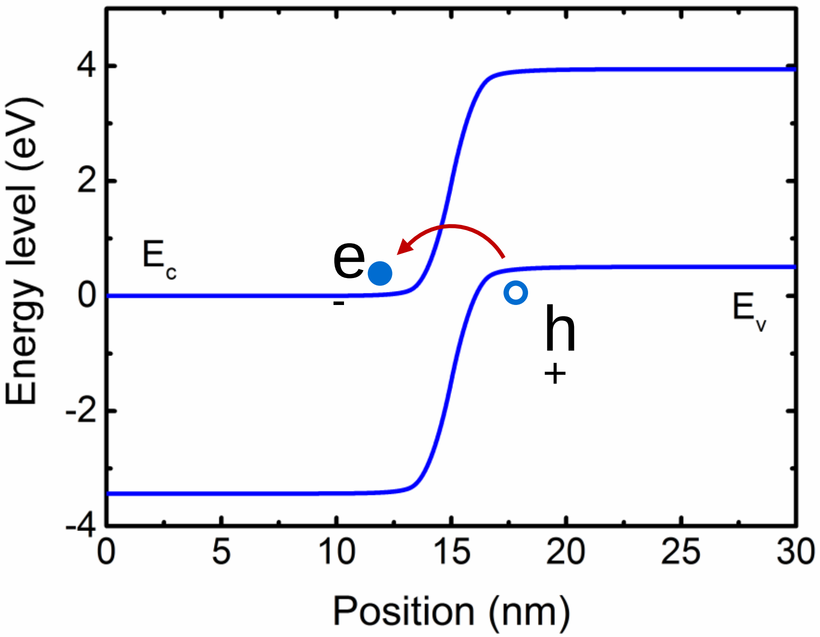


Multiple patents pending

- Combination of MOCVD and MBE allows for high quality MOCVD InGaN active regions with high doping density of MBE
- p-type GaN is activated under NH_3 MBE growth conditions

Tunnel Junction LEDs

15 nm n-GaN 1×10^{20} cm^{-3} Si
15 nm p-GaN 2×10^{20} cm^{-3} Mg



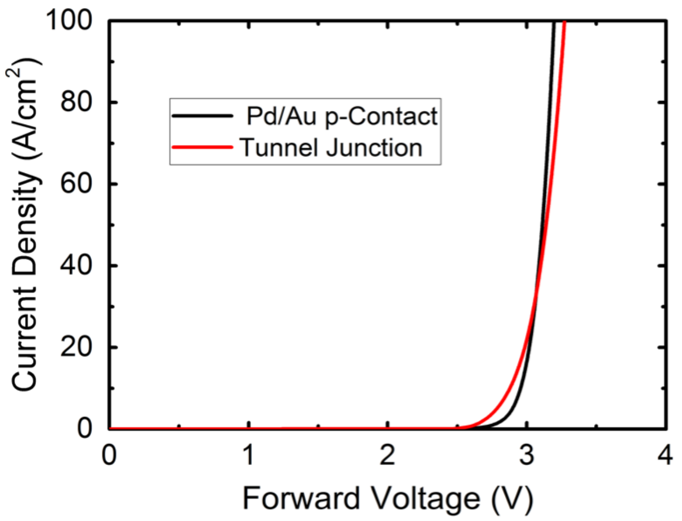
-0.5 V Bias

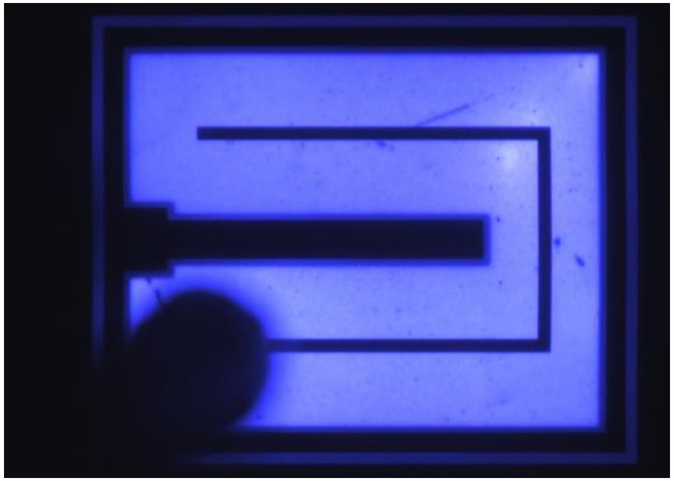
tunneling distance ~5.5 nm

Electrons tunnel directly from valence band in p-type layer to conduction band in n-type layer

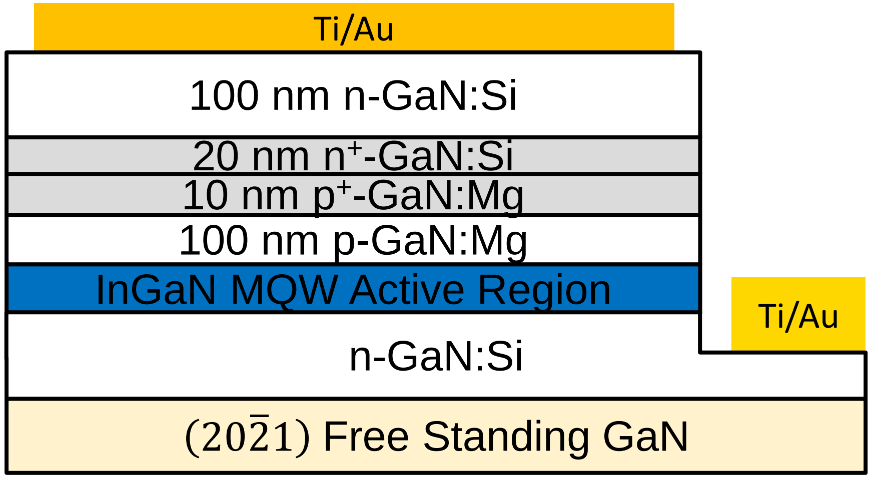
Reverse bias operation decreases tunnel distance

TJ $(20\bar{2}1)$ LED





0.1 mm^2 chip at 20 A/cm^2



Ti/Au

100 nm n-GaN:Si

20 nm n$^+$-GaN:Si

10 nm p$^+$-GaN:Mg

100 nm p-GaN:Mg

InGaN MQW Active Region

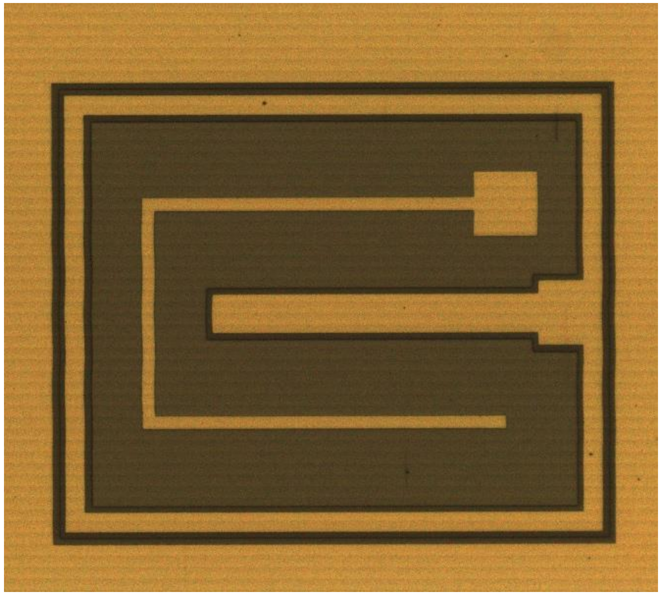
Ti/Au

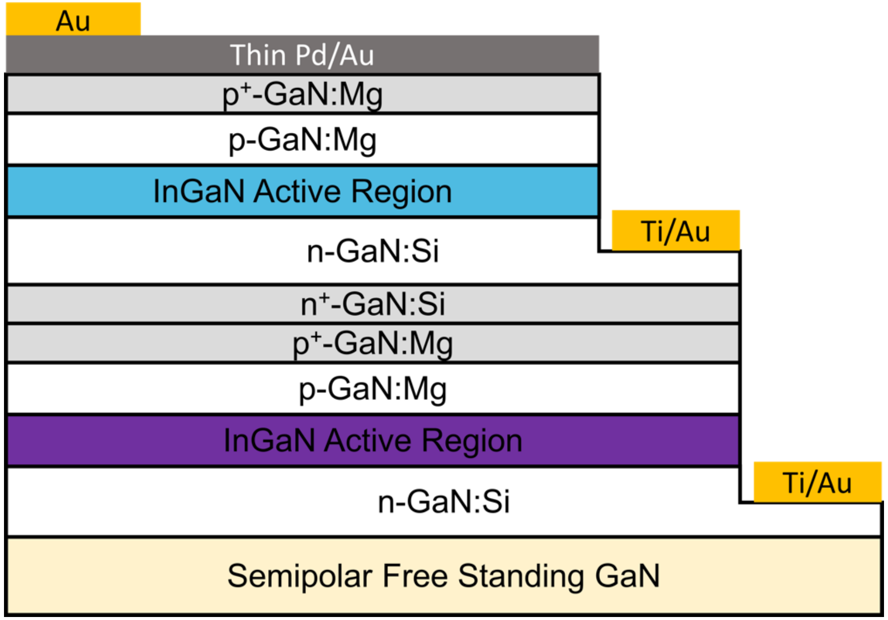
n-GaN:Si

$(20\bar{2}1)$ Free Standing GaN

- Small area LED highlight voltage drop in tunnel junction
- LED with small n-contact illustrates current spreading abilities

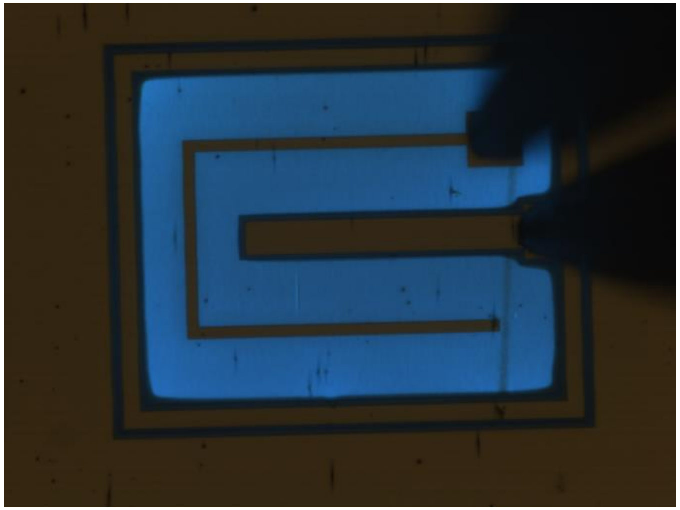
Multi-Junction LEDs (Triple Contact Design)

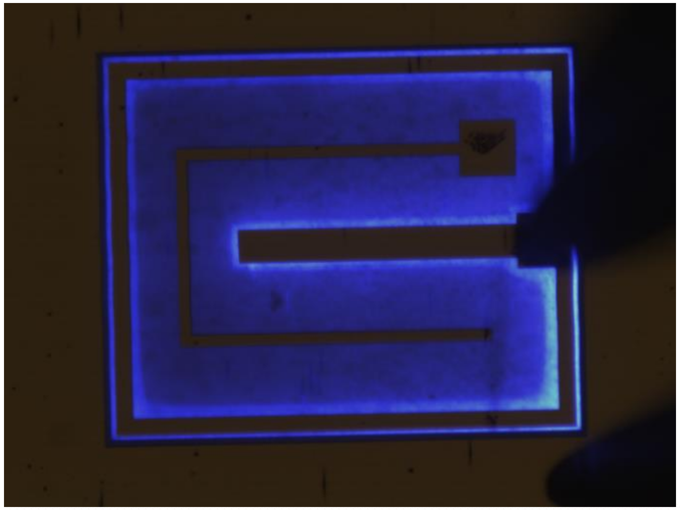


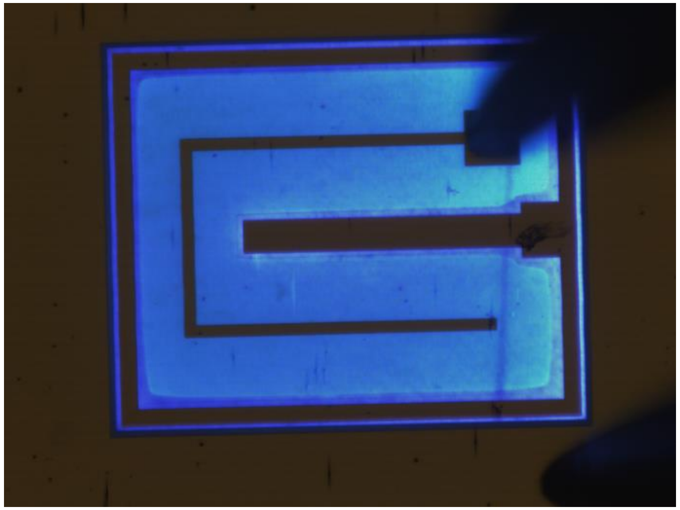


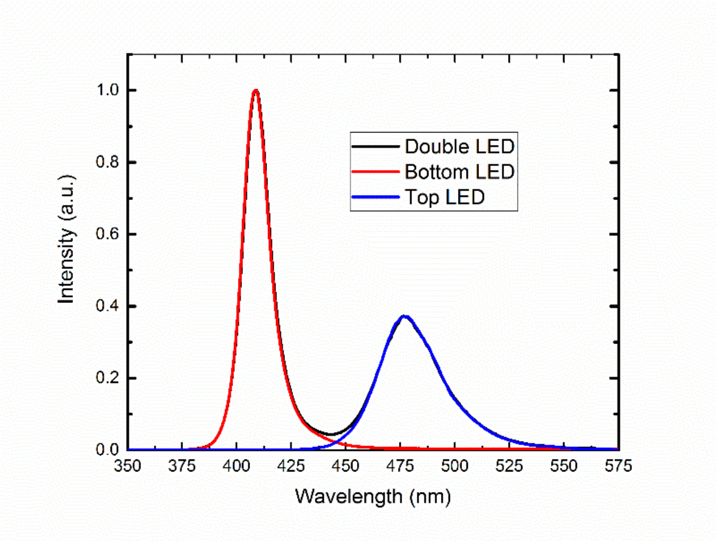
- Thin metal current spreading layer for top LED
- Two contacts so each active region can be operated independently or in series

Dual Wavelength $(20\bar{2}1)$ LEDs

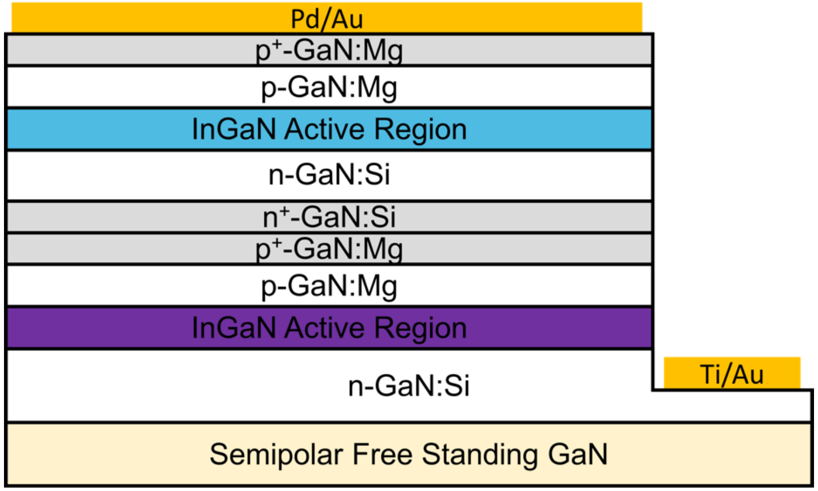


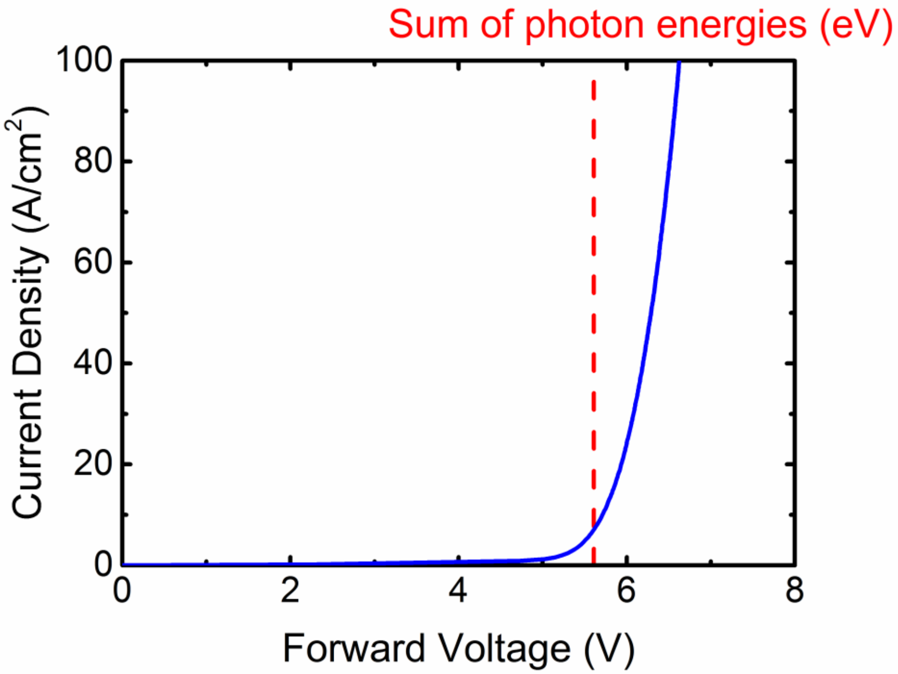






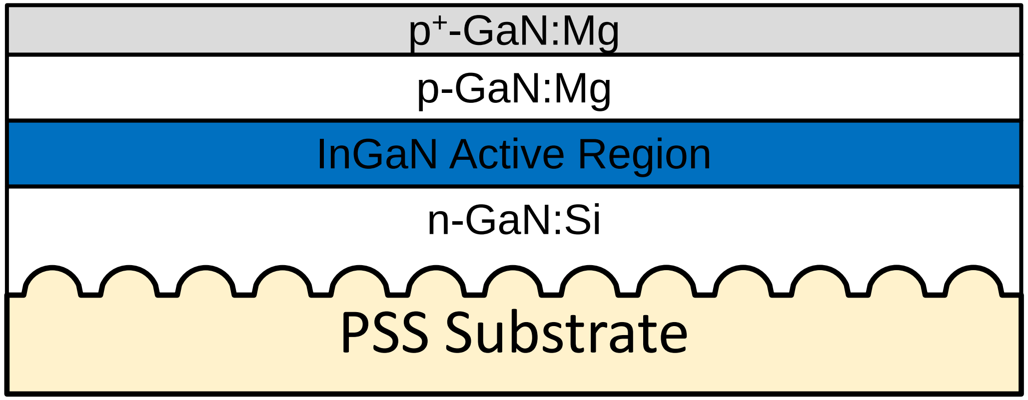
Multiple Junction LED Voltage





- LED turns on near sum of photon energies

Patterned Sapphire Substrate LEDs



p^+-GaN:Mg

p-GaN:Mg

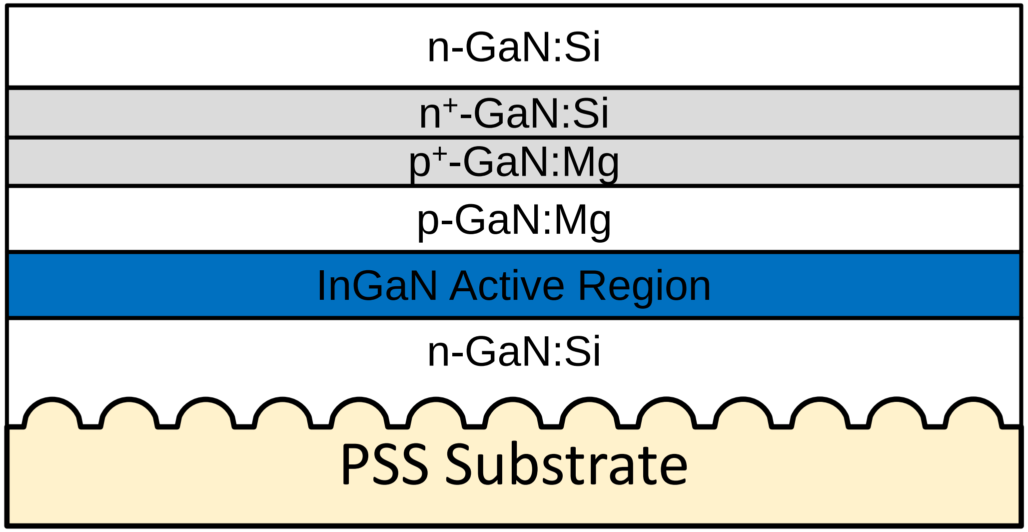
InGaN Active Region

n-GaN:Si

PSS Substrate

- c-plane PSS LEDs are industry standard for LEDs
- Pattern improves light extraction and LED quality

Patterned Sapphire Substrate LEDs



n-GaN:Si

n^+-GaN:Si

p^+-GaN:Mg

p-GaN:Mg

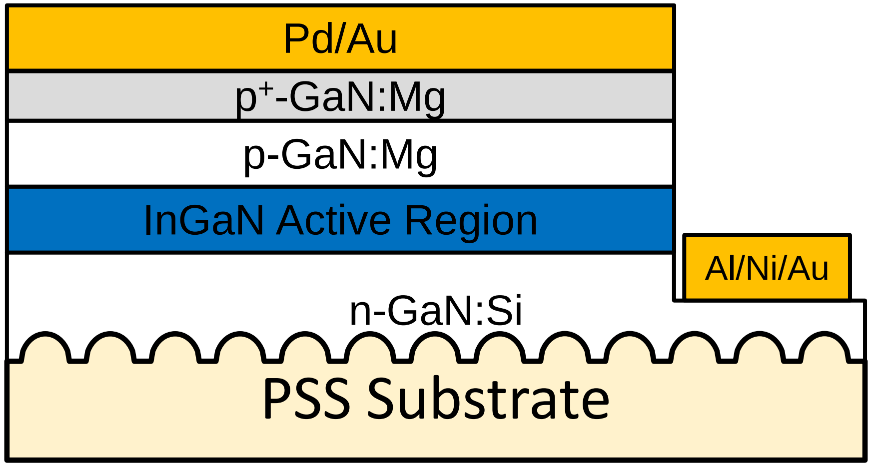
InGaN Active Region

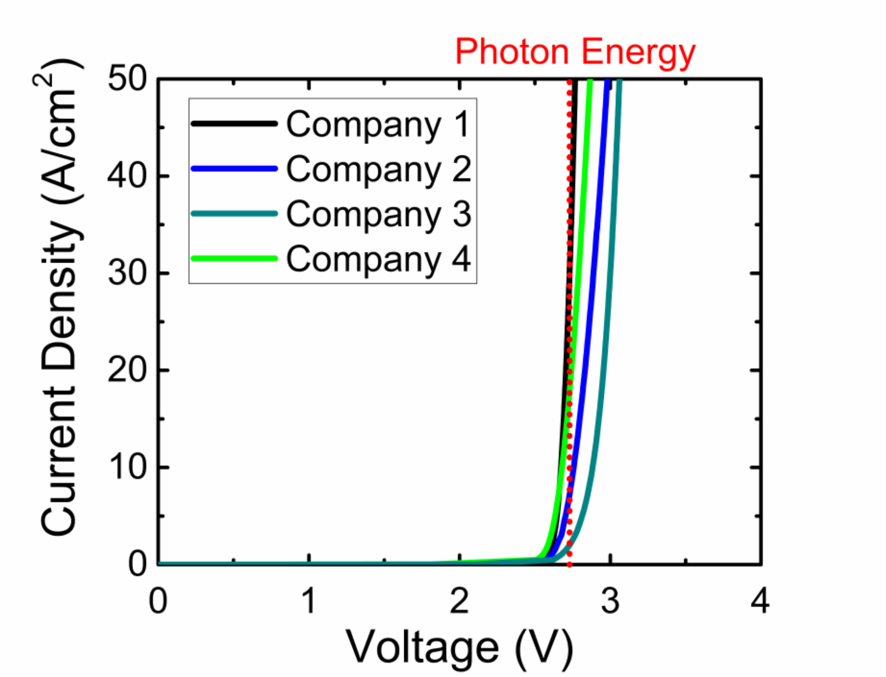
n-GaN:Si

PSS Substrate

- c-plane PSS LEDs are industry standard for LEDs
- Pattern improves light extraction and LED quality

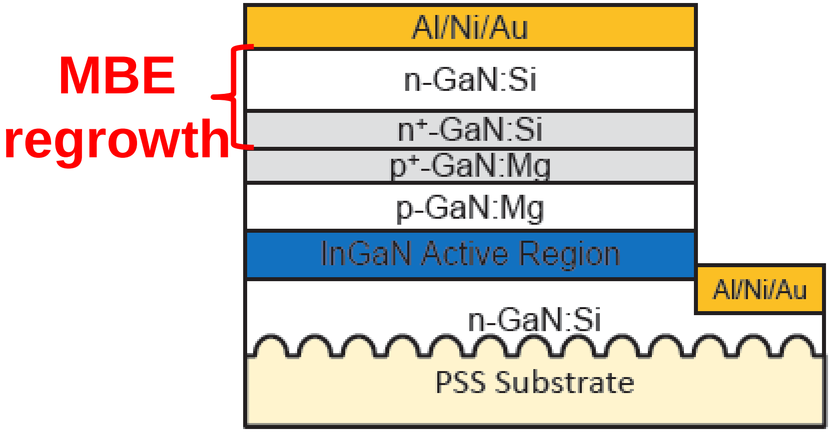
Patterned sapphire LED epi-wafers

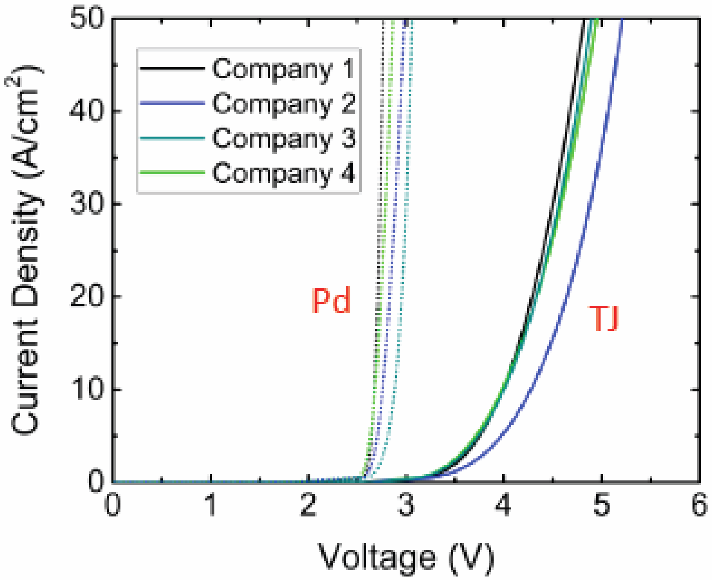




- *c-plane* PSS LEDs are industry standard for LEDs
- Pattern improves light extraction and LED quality

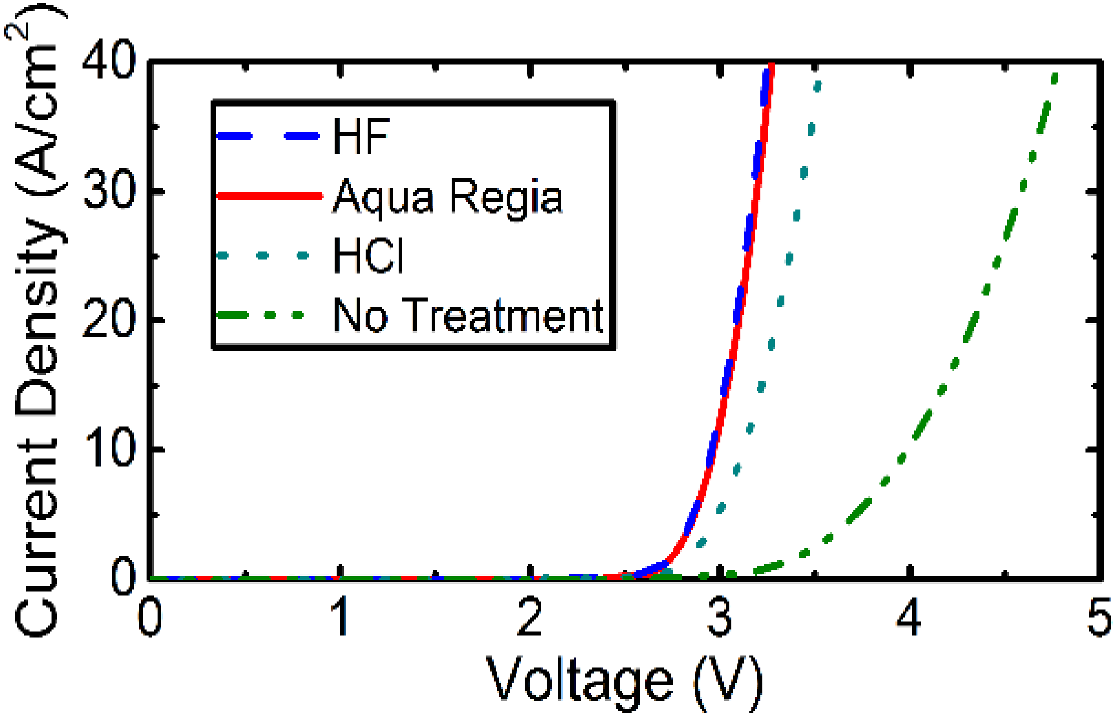
Tunnel junction regrowths





- Initial tunnel junction devices had higher voltages compared with reference samples than devices on nonpolar and semipolar planes

Acid treatments prior to regrowth



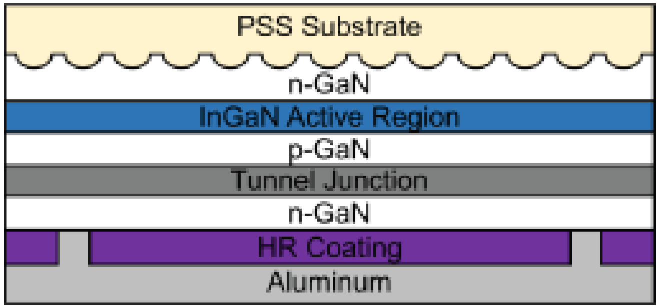
- *HF treatment provides lowest voltage for c-plane TJs*

3.08 V at 20 A/cm^2

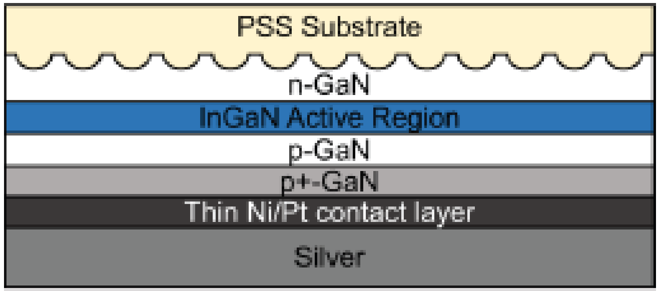
Patent Pending: “III-Nitride tunnel junction improvement through reduction of the magnesium memory effect”

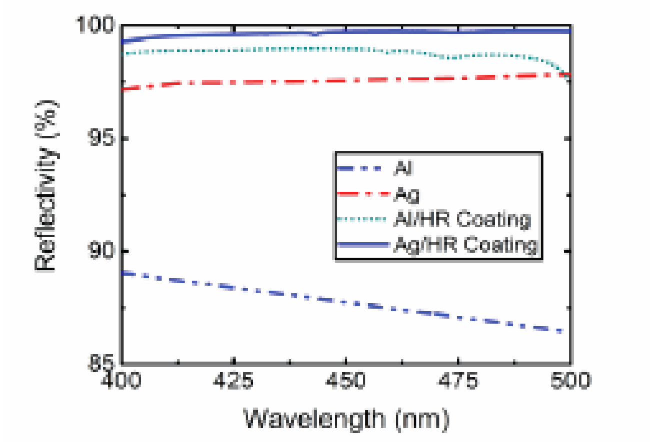
TJ Flip chip LEDs

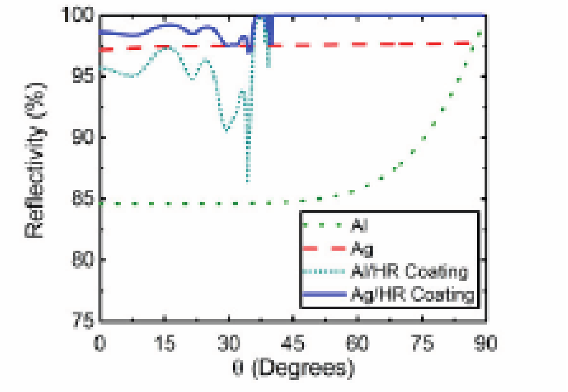
TJ Flip Chip LEDs



Conventional Flip Chip LEDs

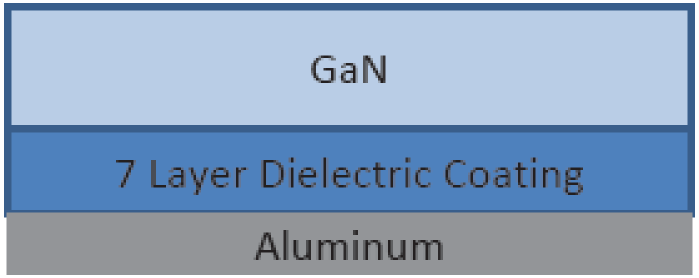


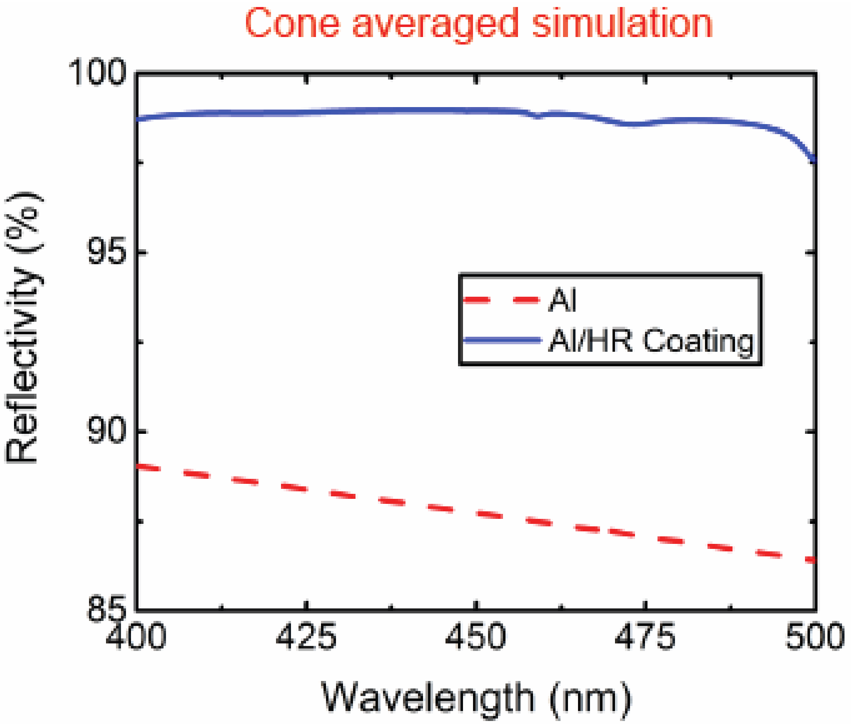




- Omnidirectional reflector has higher reflectivity than silver
- Only a small fraction of aluminum contact area is needed

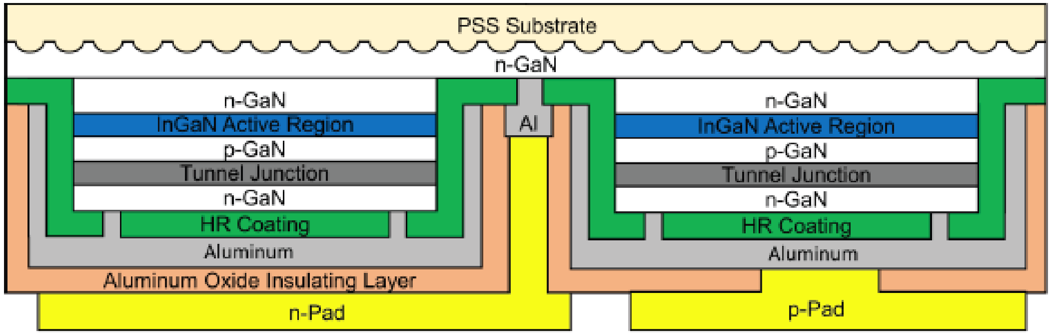
High reflectivity coating

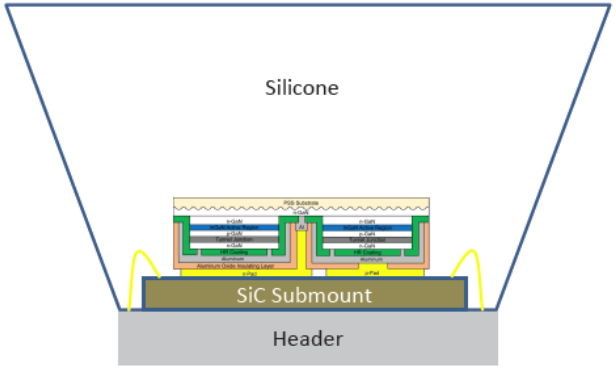



Cone averaged simulation

- Multilayer dielectric coating under wire bond pads increases reflectivity to over 97%

Flip chip LED design





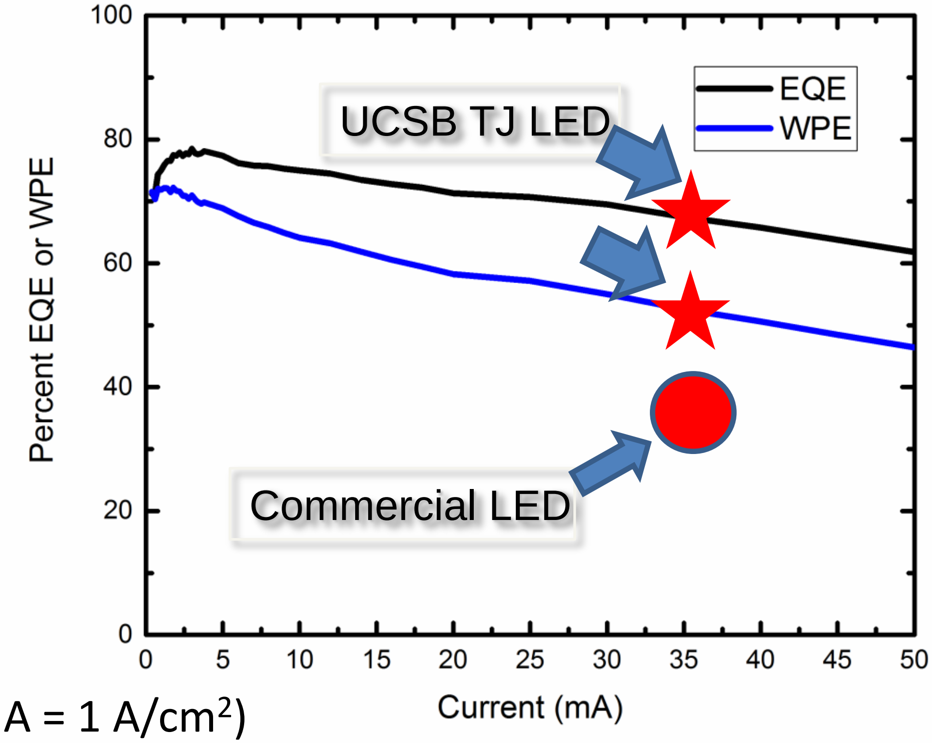
- HR coating and metal surrounds mesa to reflect more light
- LEDS are flipped onto a patterned SiC submount
- Wire bonded to header

Patent Pending: “III-Nitride flip chip LED with dielectric based mirror”

Tunnel Junction Blue LED

Peak EQE 78%, peak WPE 72%

World Record-Low Droop compared to commercial LED

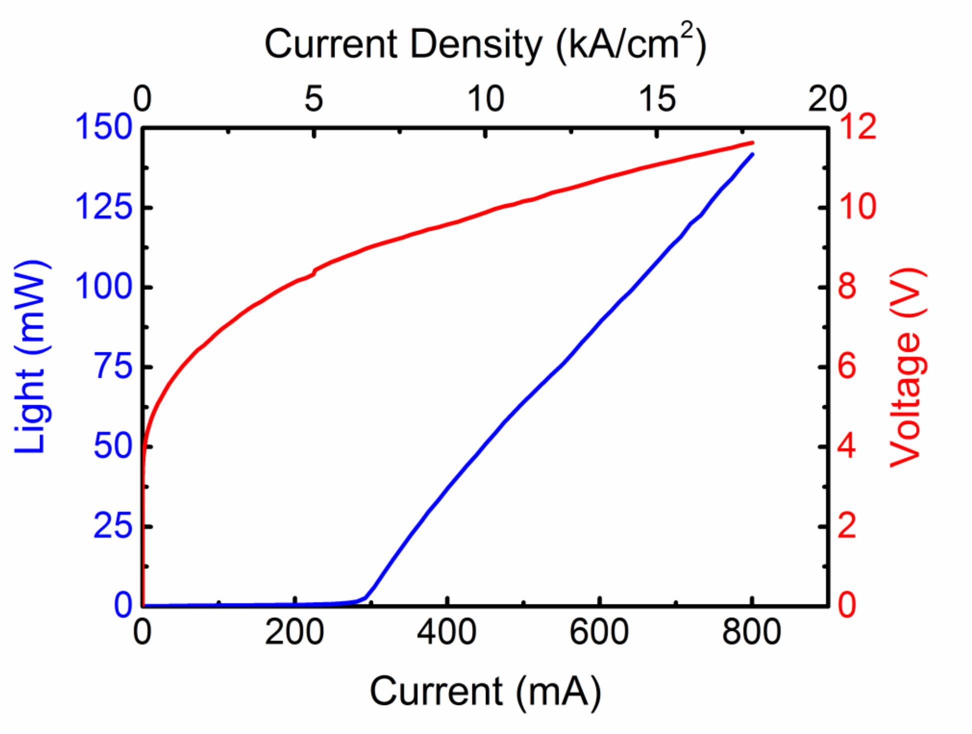


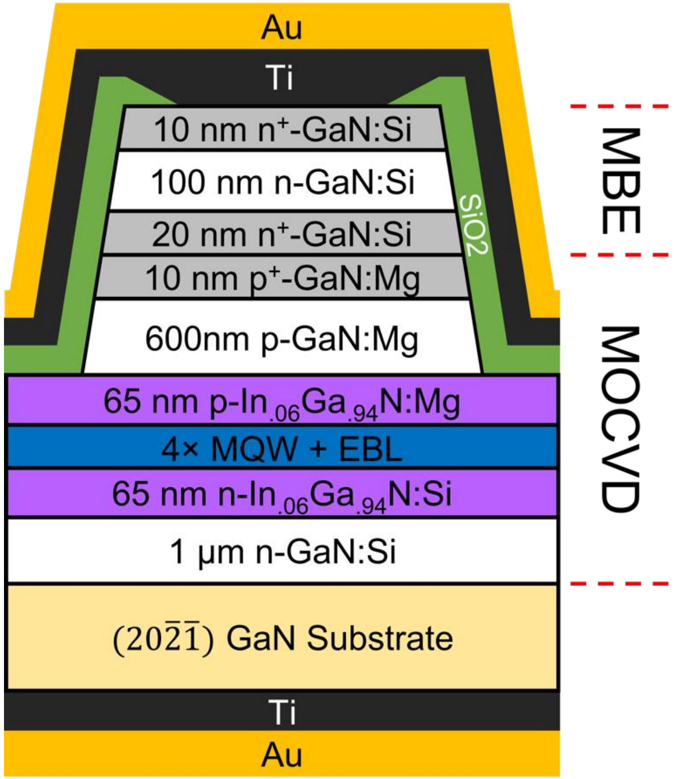
0.1 mm^2 (1 mA = 1 A/cm^2)

“Silver free III-nitride flip chip LED with wall plug efficiency over 70% utilizing GaN tunnel junction”
B.P. Yonkee, E.C. Young, S.P. DenBaars, S. Nakamura and J. S. Speck, Apply. Phys. Lett., 109

Tunnel Junction Edge Emitting Laser

1800 um by 2.5um Laser Dimension

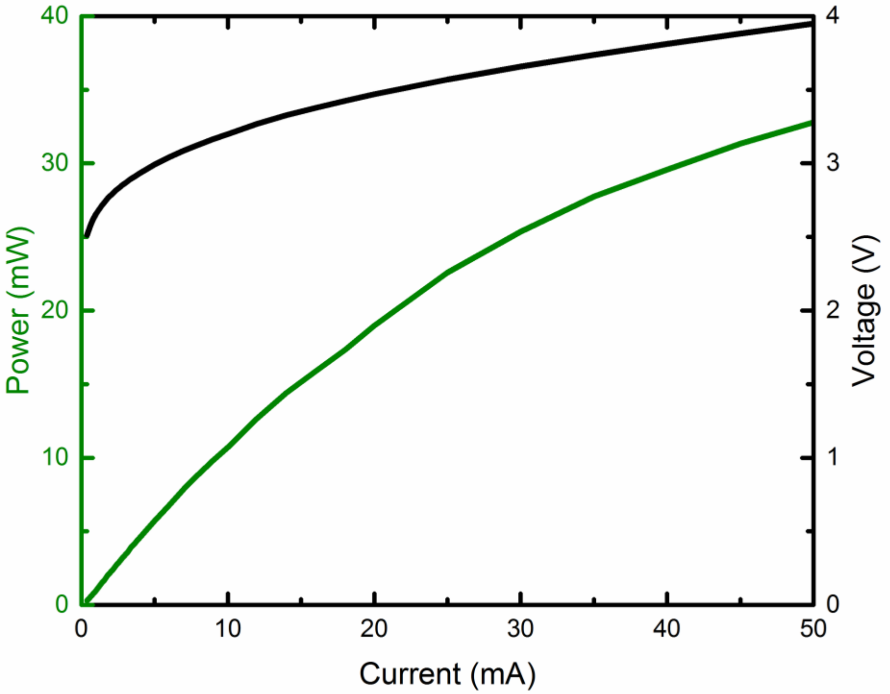


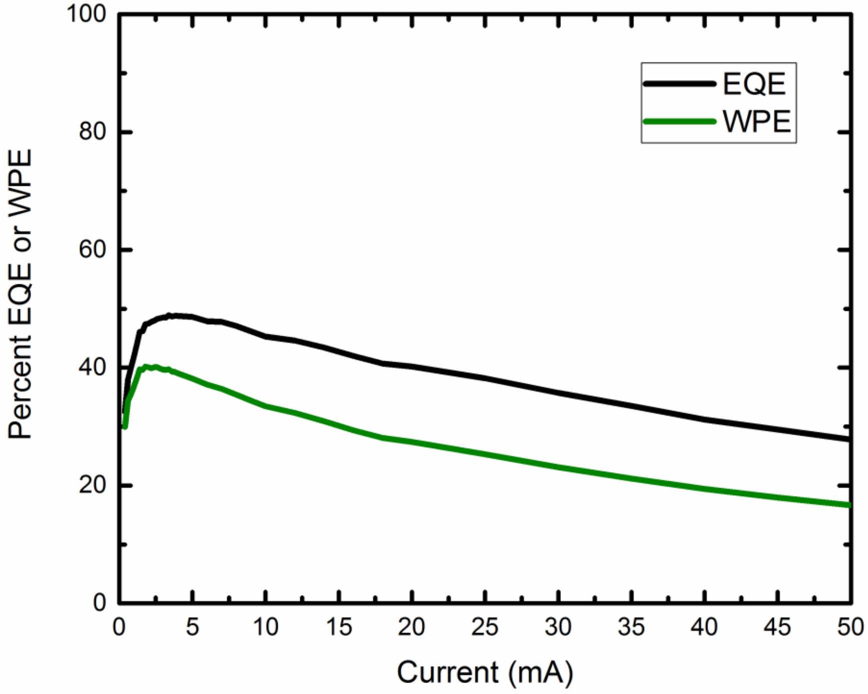


- Tunnel junction could allow for novel laser designs employing n-GaN cladding on both sides
- Highly doped p-GaN has a resistivity of ~ 1 Ωcm, giving 1 × 10^{-5} Ωcm^2 resistivity per 100nm p-GaN
- Lower doping used for low optical loss gives higher resistivity

Tunnel-junction 525 nm Green LEDs on PSS

Commercial PSS green LED epi-wafer



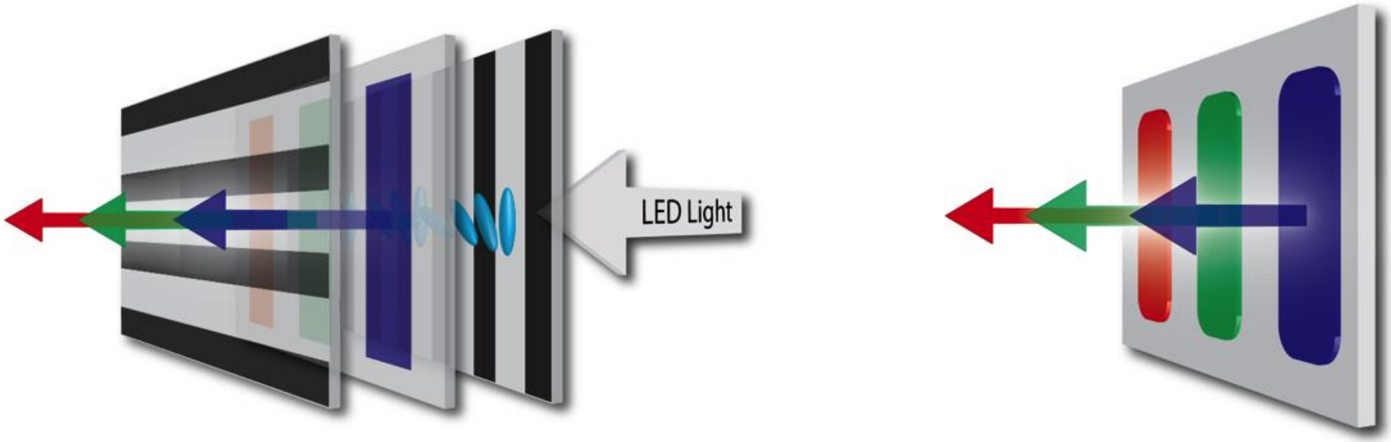


0.1 mm^2 (1 mA = 1 A/cm^2)

Peak EQE 50%, peak WPE 40%

LED Lighting: Micro LED, and Green LED for Red LED

Displays are extremely energy inefficient.



Liquid Crystal Display

Efficient Light Source

\+ Inefficient Filtering Process

5% Light Out

(95% Power Lost)

Organic LED Display

No Filtering Process

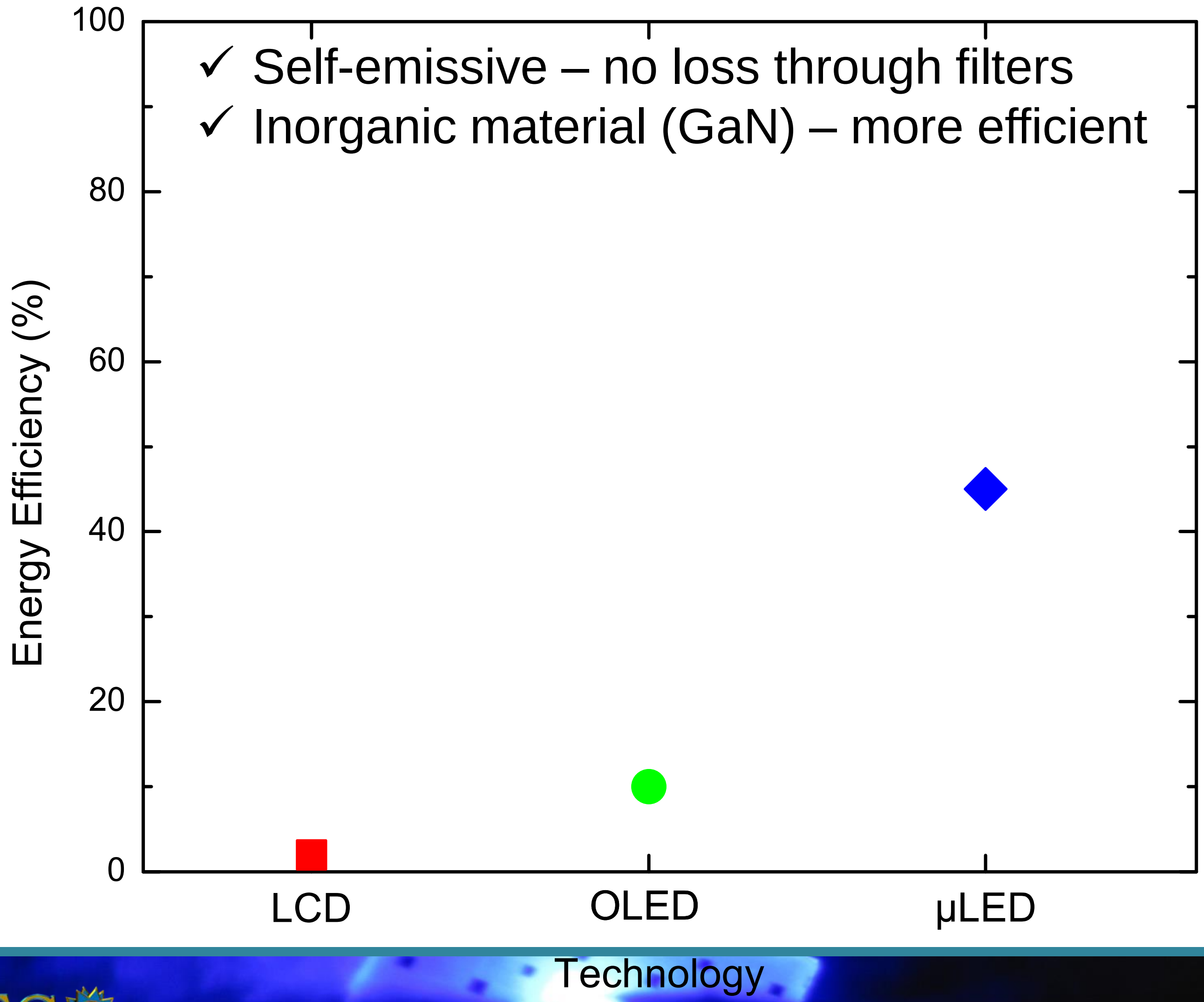
\+ Inefficient Light Source

10% Light Out

(90% Power Lost)

Figure courtesy of Chris Pynn
n

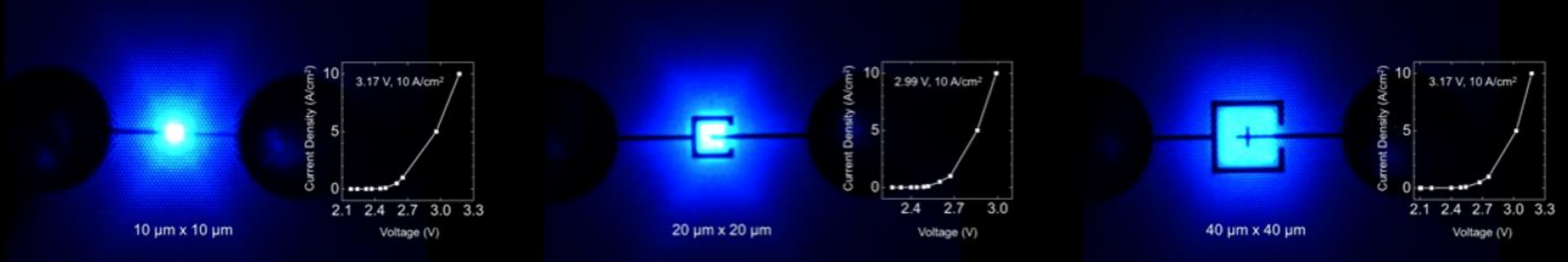
RGB µLED displays can be much more efficient.


- ✓ Self-emissive – no loss through filters
- ✓ Inorganic material (GaN) – more efficient

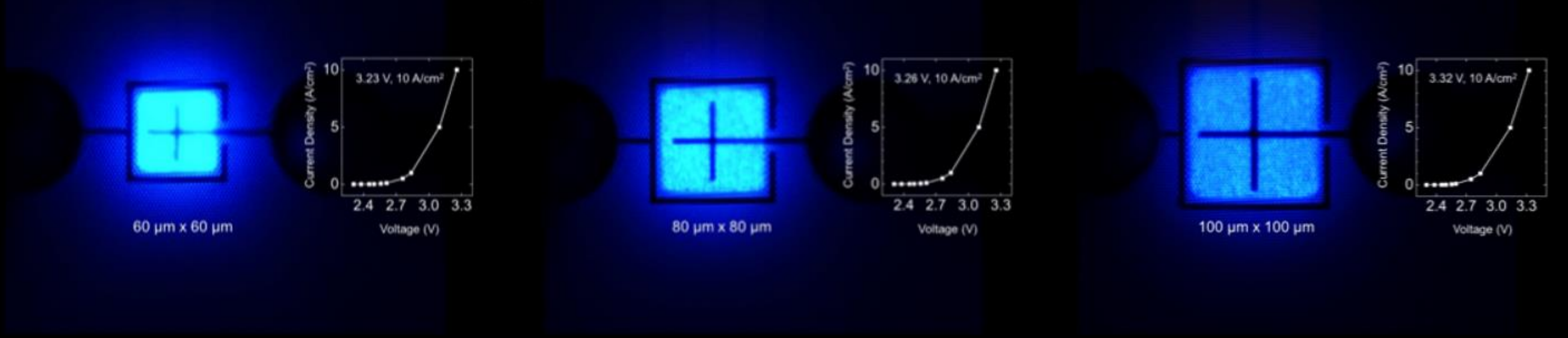
Electroluminescence reveals emission patterns.

10 A/cm^2

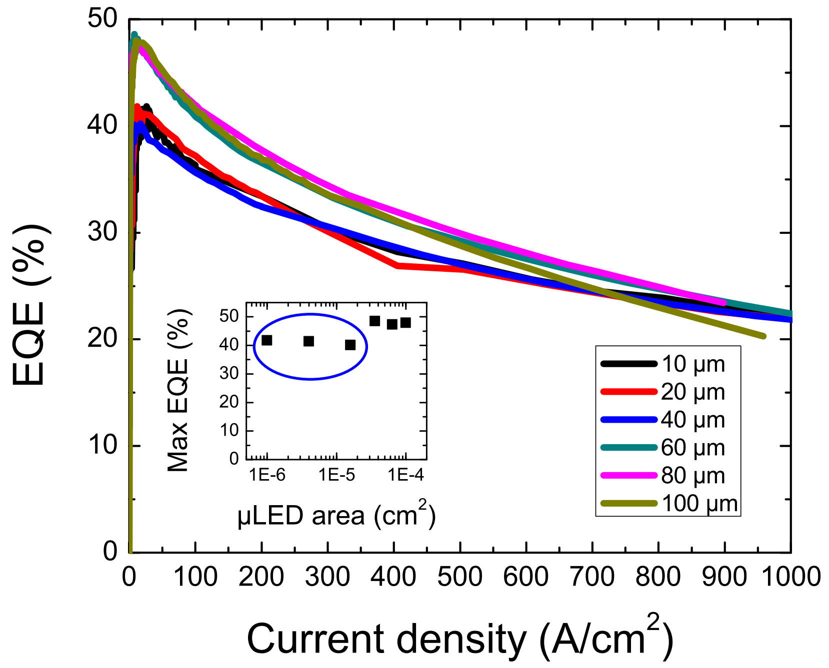
Smaller µLEDs have less area over which to spread current.

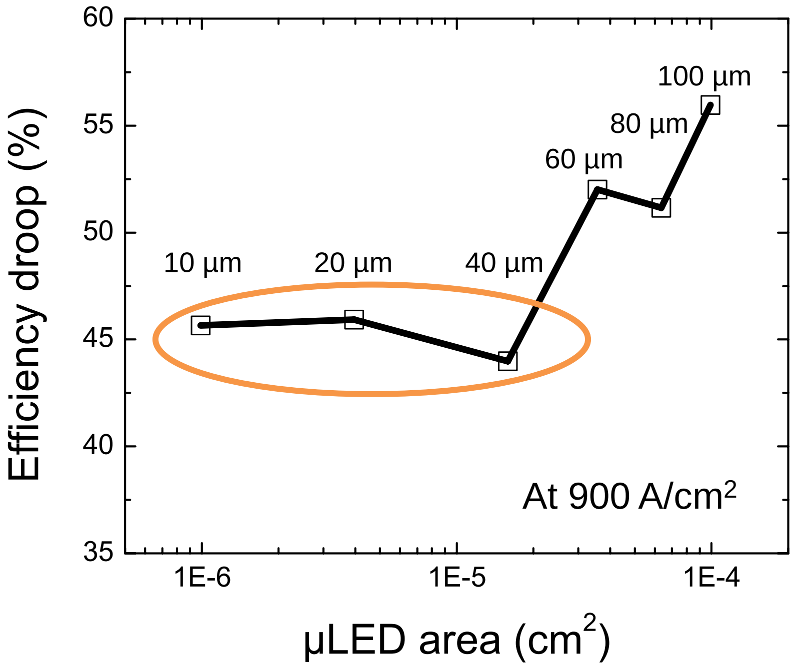


Current crowds around the edges of larger LEDs at low current densities.



Small µLEDs maintain high EQE.

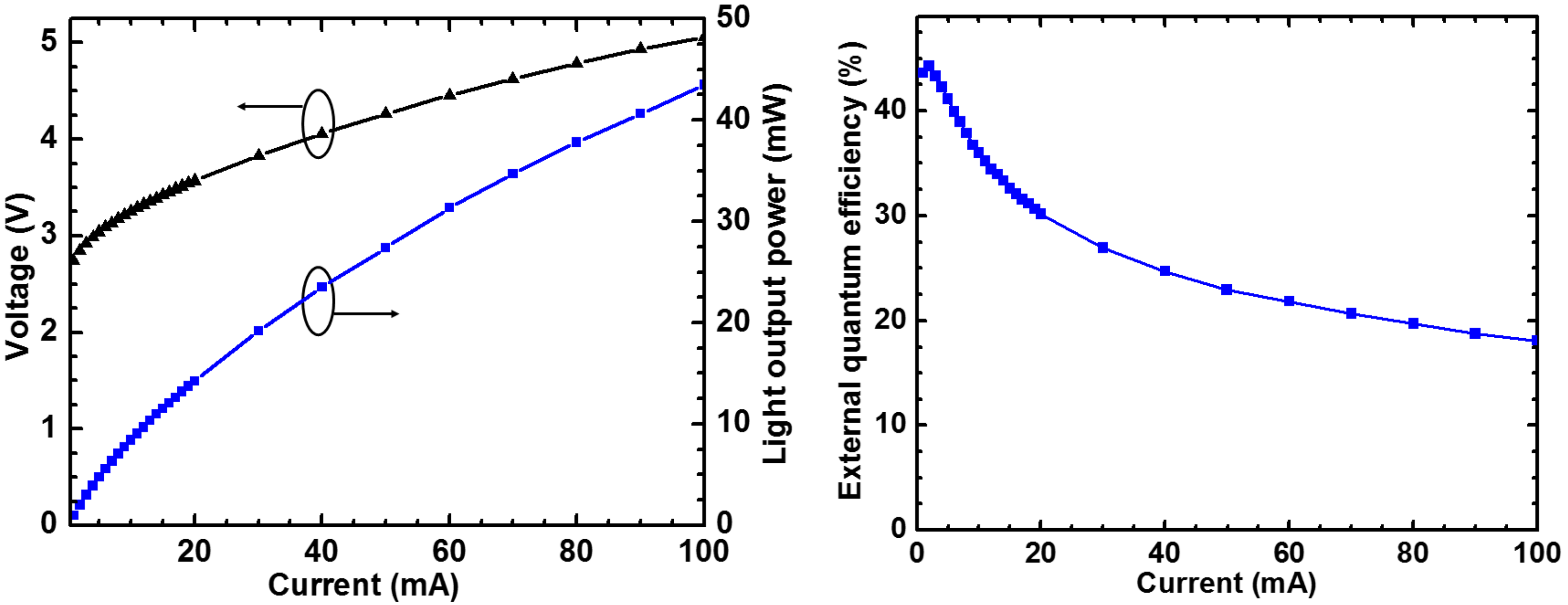




- The max EQE for all µLEDs **are similar (40-50%).**
- Reduction of the EQE is due to **sidewall damage** as µLEDs have higher perimeter to area ratios.
- Smaller µLEDs exhibit less droop,

Growth of Green LEDs with 3 Step Active Region

Previous high efficiency green LED



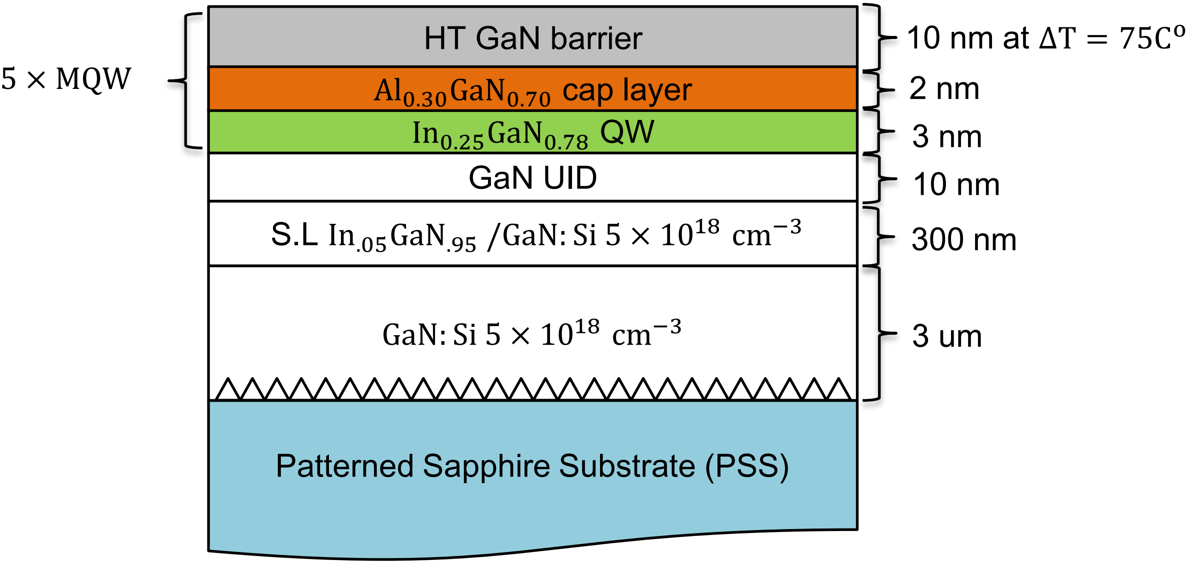
0.1 mm^2 (1 mA = 1 A/cm^2)

	Current (mA)	Voltage (V)	Wavelength (nm)	EQE%	FWHM (nm)
Packaged LED	20	3.54	526.6	30.2	33

A.Alhassan et al., Optics Express. **24**(16), 17868-17873 (2016)

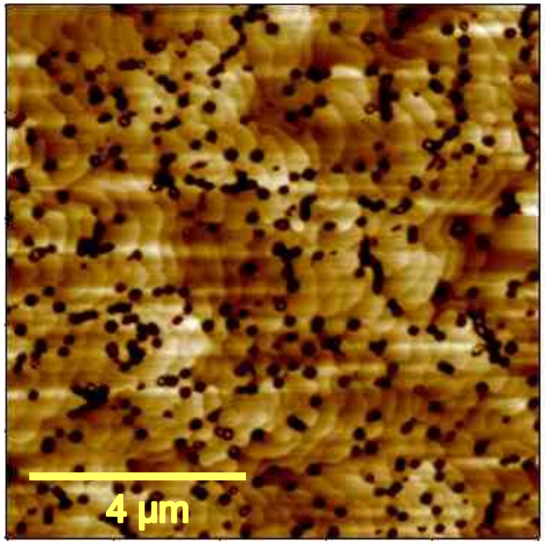
Active region study

- Further study of the surface morphology of MQW



	Layer	Thickness
$5 \times \mathrm{MQW}$	HT GaN barrier	10 nm at $\Delta T = 75C^o$
	$Al_{0.30}GaN_{0.70}$ cap layer	2 nm
	$In_{0.25}GaN_{0.78}$ QW	3 nm
	GaN UID	10 nm
	S.L $In_{.05}GaN_{.95}$ /$GaN: Si\ 5 \times 10^{18}\ cm^{-3}$	300 nm
	$GaN: Si\ 5 \times 10^{18}\ cm^{-3}$	3 um
	Patterned Sapphire Substrate (PSS)	

Pits ~ 6e8 cm^{-2}



Atomic-force microscopy (AFM) scan of the last GaN barrier

- High density of v-defect in green MQW

Understanding V-defect problem

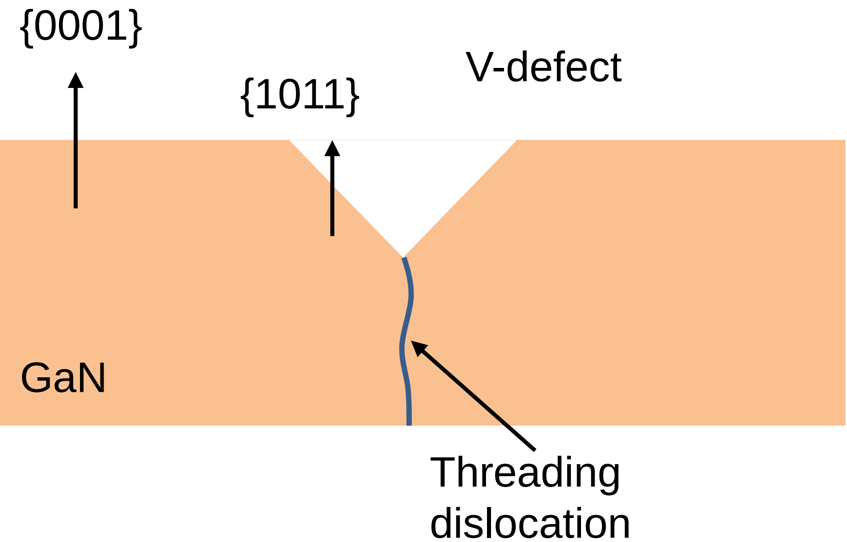
- V-defect initiates at threading dislocation (TD).
- Kinetically controlled by reduced Ga incorporation which is the primary cause for V-defect.
    - Growth rate of {0001} plane > {1011} planes

☐ Increase surface mobility to overcome the problem.

- Lower V/III ratio.
- Higher temperature.
- H_2 carrier gas.

Limitation.

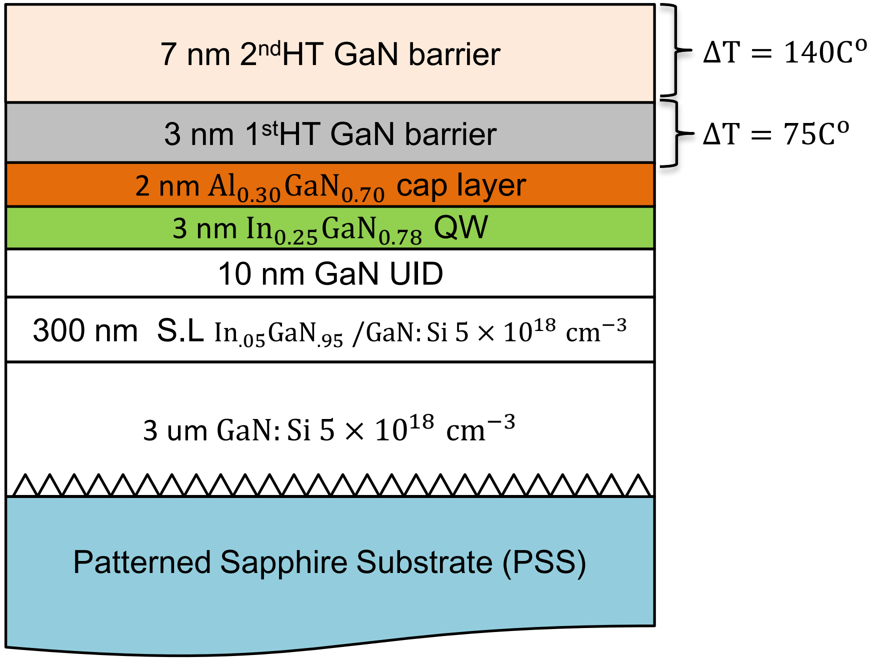
- Temperature difference $\Delta\mathrm{T} = 75^{\mathrm{o}}\mathrm{C}$.
- Thin GaN barrier.



Cross-sectional schematic of V-defect

3 step Active region

- Growth of Active region in 3 steps with different carrier gas.
  - QW and AlGaN cap layer growth in N2 environment.
  - 1stHT GaN barrier with H_2(200 sccm)+N_2(1.9 slm) at $\Delta T = 75C^o$.
  - 2ndHT GaN barrier with H_2(1.9 slm)+N_2(1.9 slm) at $\Delta T = 140C^o$.



7 nm 2ndHT GaN barrier — $\Delta T = 140C^o$

3 nm 1stHT GaN barrier — $\Delta T = 75C^o$

2 nm $Al_{0.30}GaN_{0.70}$ cap layer

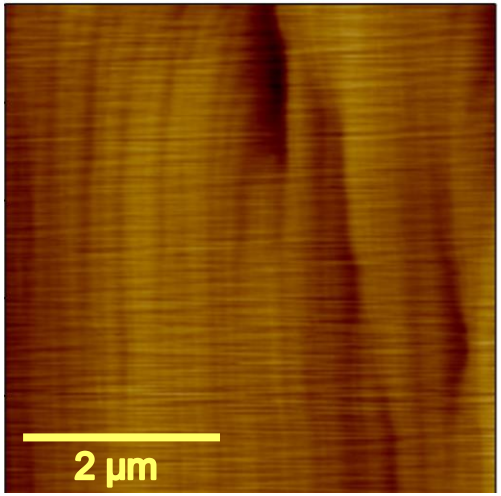
3 nm $In_{0.25}GaN_{0.78}$ QW

10 nm GaN UID

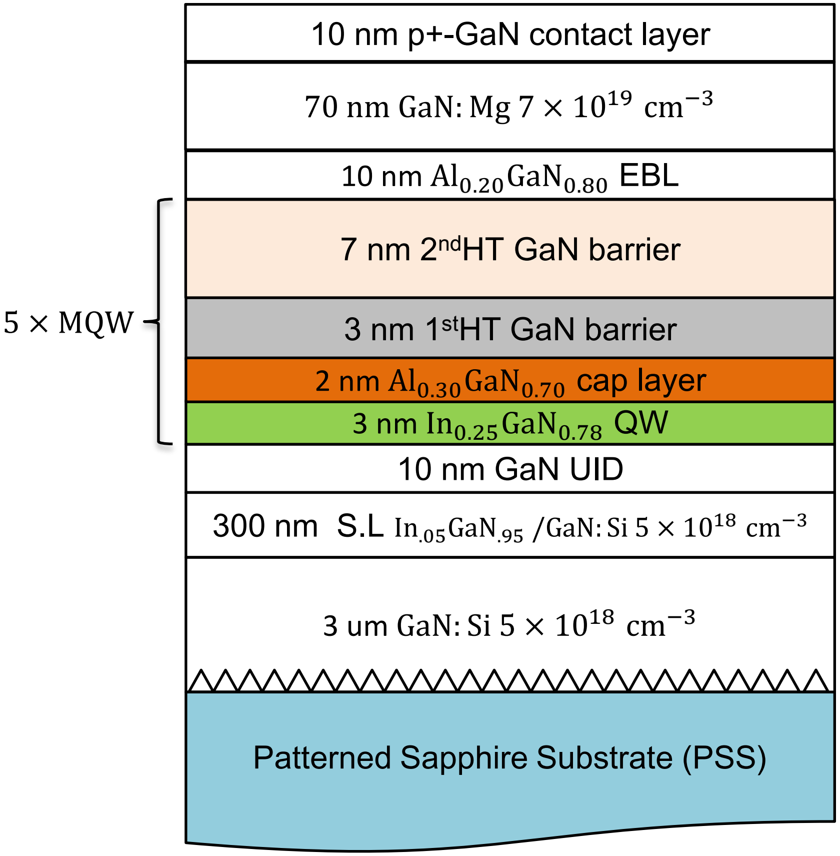
300 nm S.L $In_{.05}GaN_{.95}$ /GaN: Si 5×10^{18} cm^{-3}

3 um GaN: Si 5×10^{18} cm^{-3}

Patterned Sapphire Substrate (PSS)



Final device



10 nm p+-GaN contact layer

70 nm $\mathrm{GaN: Mg}\ 7 \times 10^{19}\ \mathrm{cm}^{-3}$

10 nm $\mathrm{Al_{0.20}GaN_{0.80}}$ EBL

7 nm 2nd HT GaN barrier

3 nm 1st HT GaN barrier

2 nm $\mathrm{Al_{0.30}GaN_{0.70}}$ cap layer

3 nm $\mathrm{In_{0.25}GaN_{0.78}}$ QW

$5 \times \mathrm{MQW}$

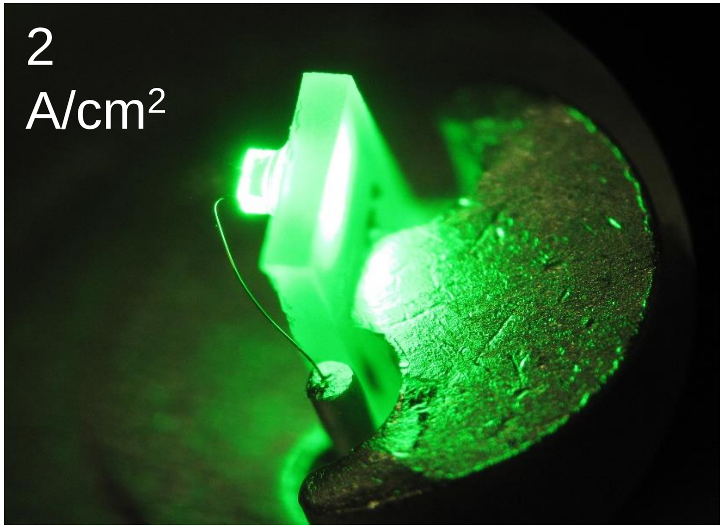
10 nm GaN UID

300 nm S.L $\mathrm{In_{.05}GaN_{.95}\ /GaN: Si}\ 5 \times 10^{18}\ \mathrm{cm}^{-3}$

3 um $\mathrm{GaN: Si}\ 5 \times 10^{18}\ \mathrm{cm}^{-3}$

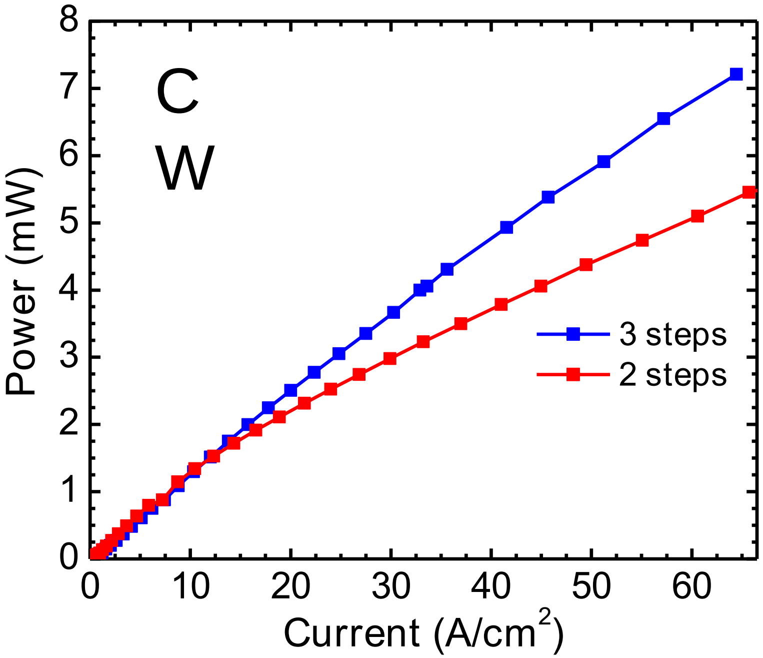
Patterned Sapphire Substrate (PSS)

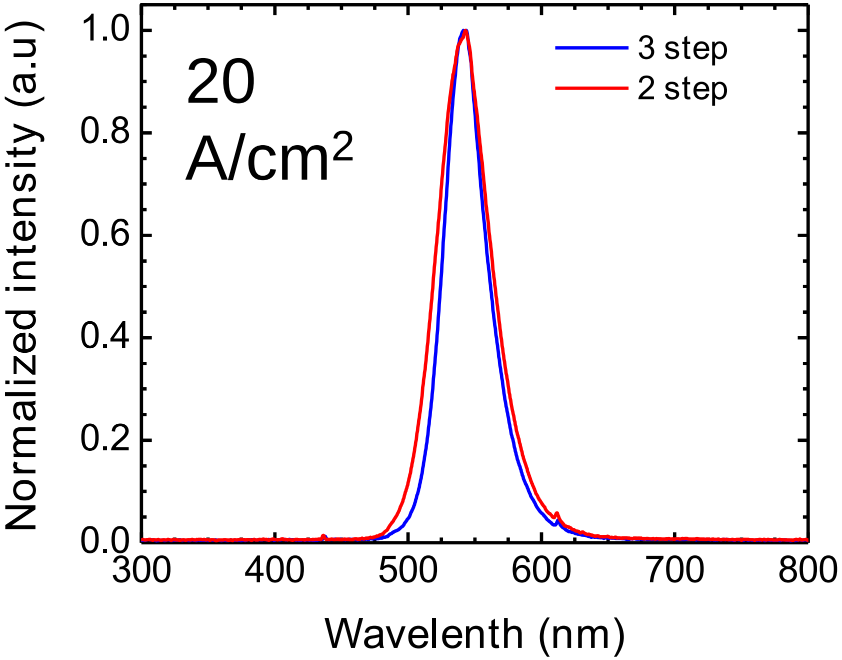
- Three steps photolithography fabrication process.
- 0.1mm^2 active area.
- Vertical transparent LEDs packaging.



3 vs 2 step Active region results

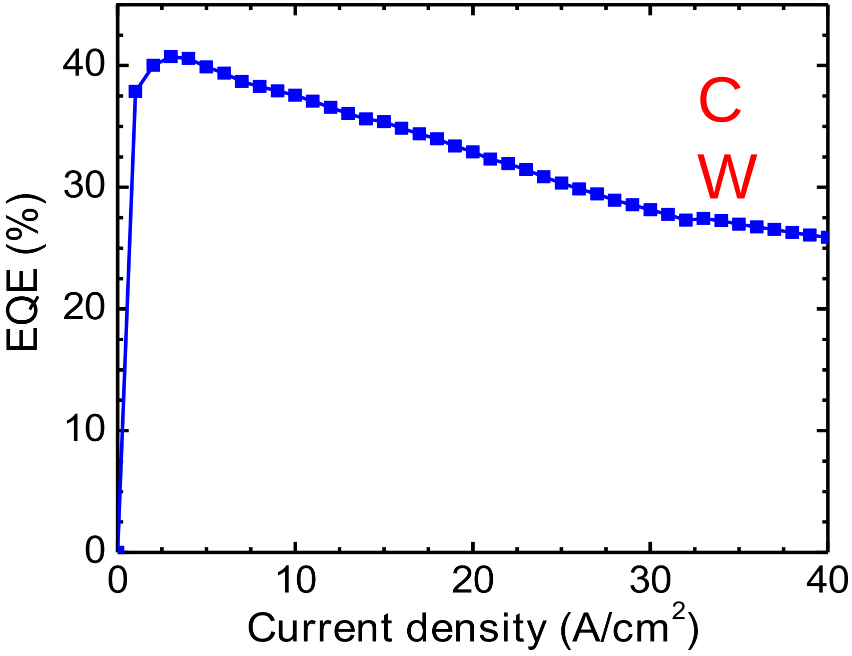
- 0.1mm^2 chip size.

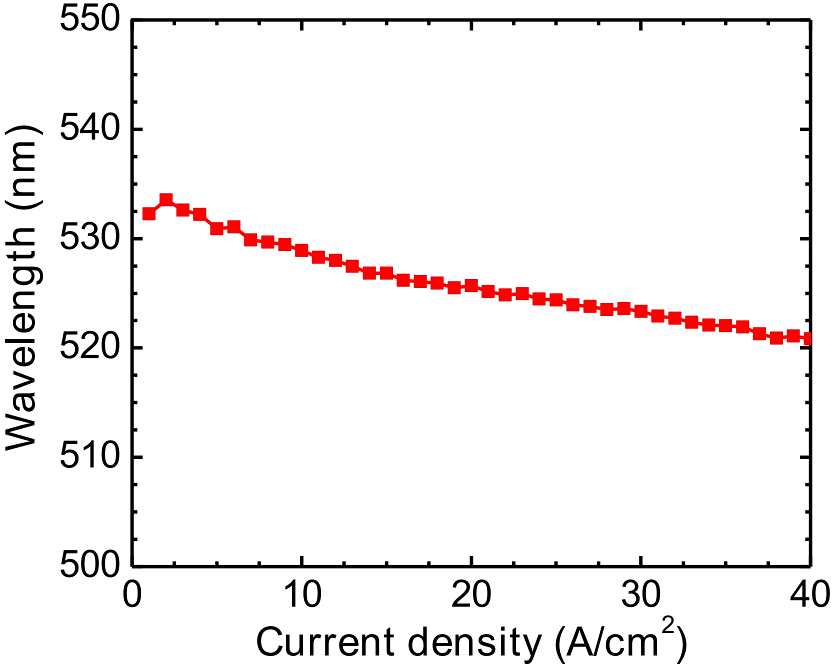




“Multi-step active region for high performance nitride LEDs” (patent pending)

Green LED results





	Current density (A/cm^2)	Voltage (V)	Wavelength (nm)	EQE%	FWHM (nm)
Packaged LED	20	4.6	525.4	33	34

Laser Lighting:
High Power Semipolar $(20\bar{2}\bar{1})$ LDs

UCSB's Vision

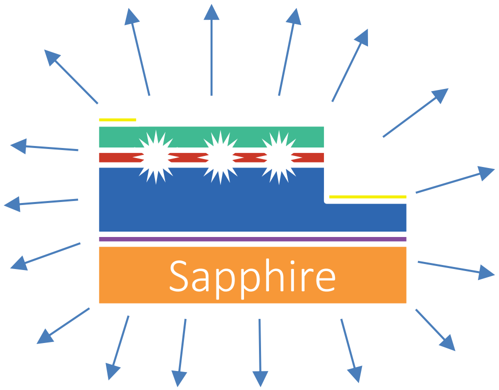
LED based White Light is great, **Laser based** is even better!

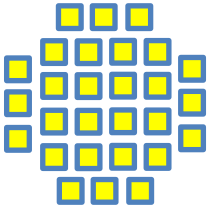
Device

60 W Incandescent Equivalent

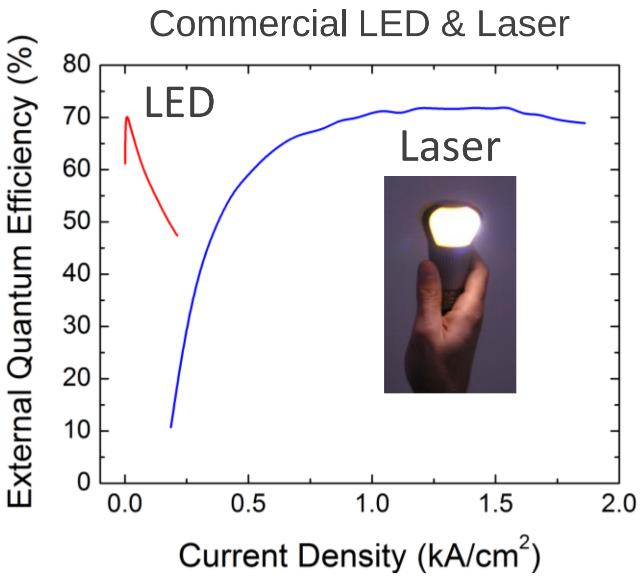
External Quantum Efficiency LED/Laser vs. Current Density

LED



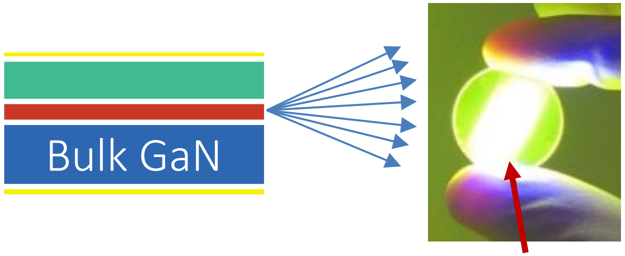


28 mm^2



M. Cantore *et al.*, UCSB

Laser



Phosphor Strip

0.3 mm^2

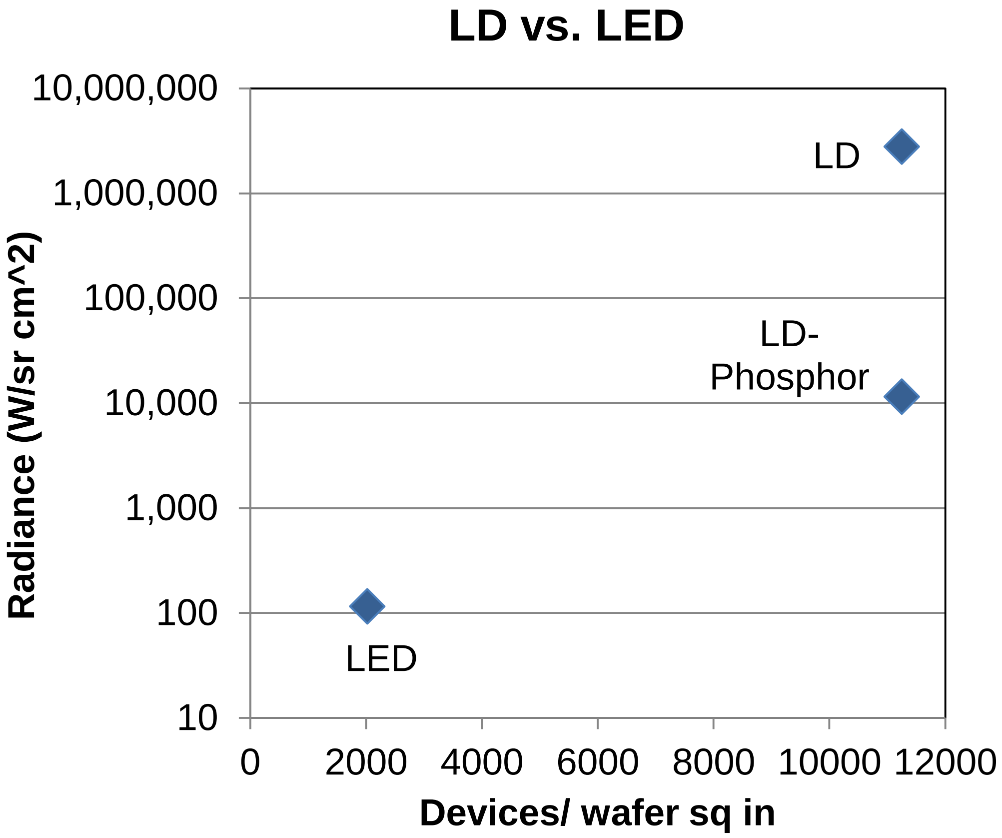
Laser Light: Game-changing Radiance

Substantially more LD devices per sq in of wafer (vs. LED)

LDs are higher brightness by several orders of mag (vs. LED)

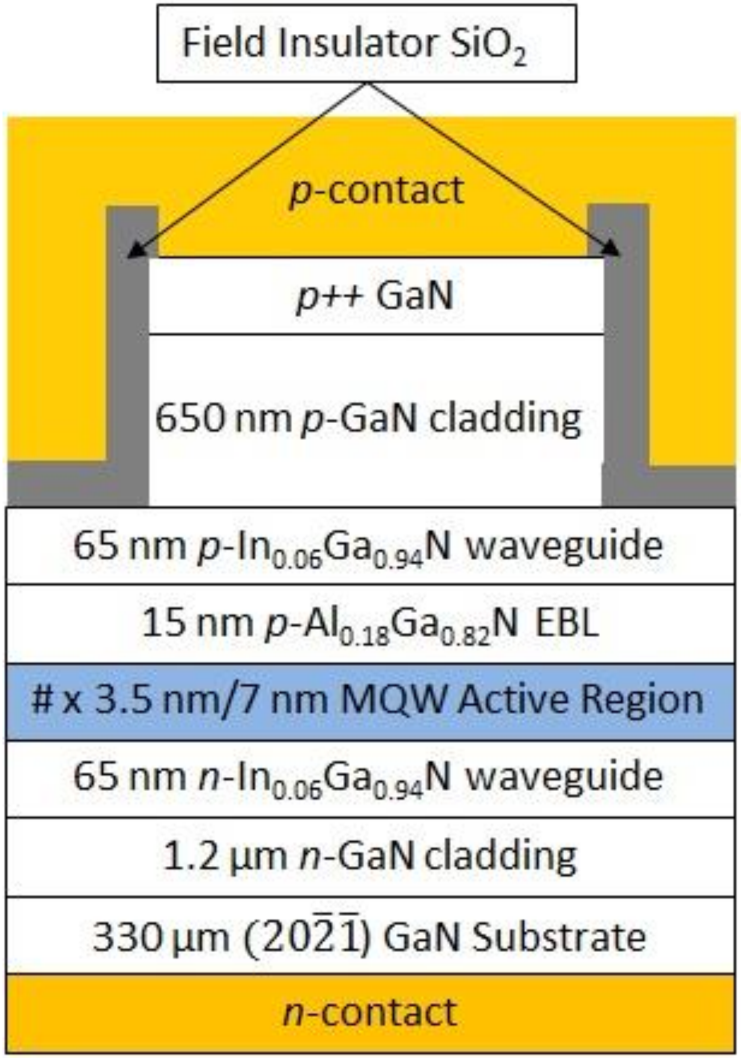
LD WPE is increasing and cost is decreasing

Small source -> simpler optics, novel phosphor designs



"Delivered" Lm/W and $/Lm for LD sources is increasingly appealing for specialty lighting applications

UCSB Blue Laser Structure



Field Insulator SiO_2

p-contact

p++ GaN

650 nm *p*-GaN cladding

65 nm *p*-$In_{0.06}Ga_{0.94}N$ waveguide

15 nm *p*-$Al_{0.18}Ga_{0.82}N$ EBL

x 3.5 nm/7 nm MQW Active Region

65 nm *n*-$In_{0.06}Ga_{0.94}N$ waveguide

1.2 µm *n*-GaN cladding

330 µm $(20\bar{2}\bar{1})$ GaN Substrate

n-contact

Becerra et al. Appl. Phys. Expr. **9**, 092104 (2016).

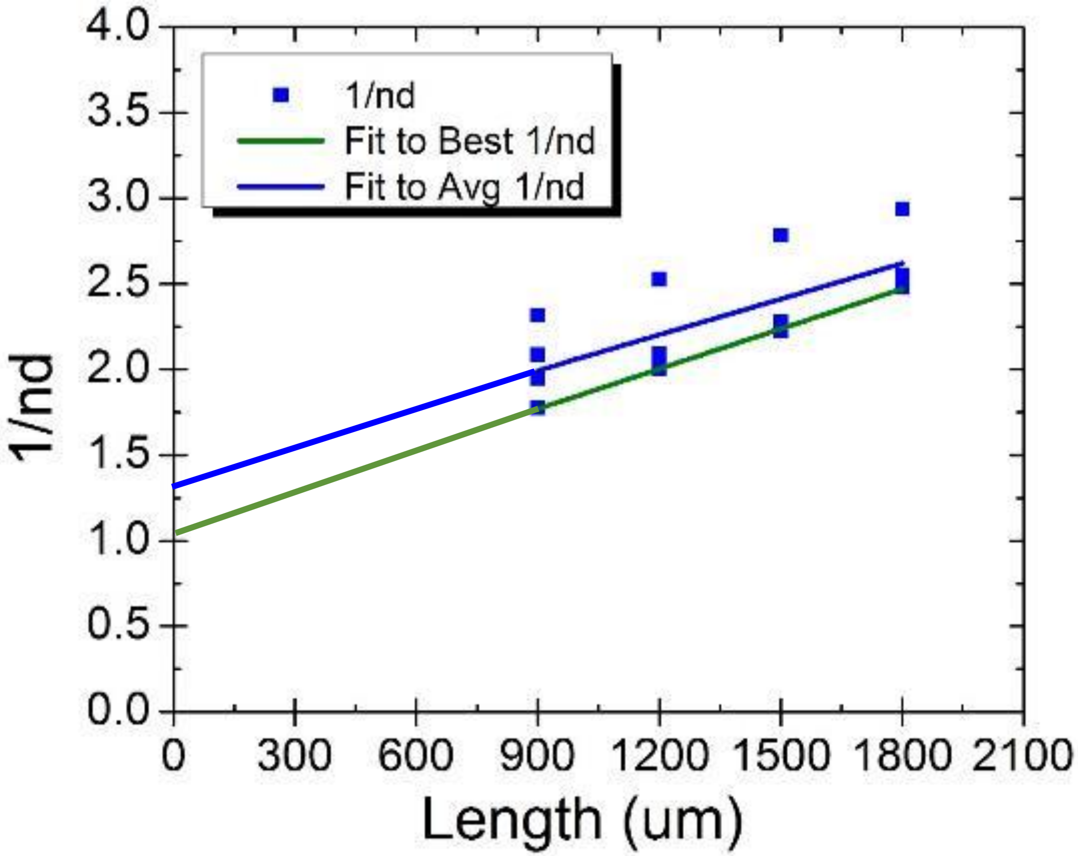
Internal Loss and η_i for $(20\bar{2}\bar{1})$ LD

$$\frac{1}{\eta_d} = \frac{\langle \alpha_i \rangle}{\eta_i ln(1/R)} L + \frac{1}{\eta_i}$$

From this fit, we calculate:

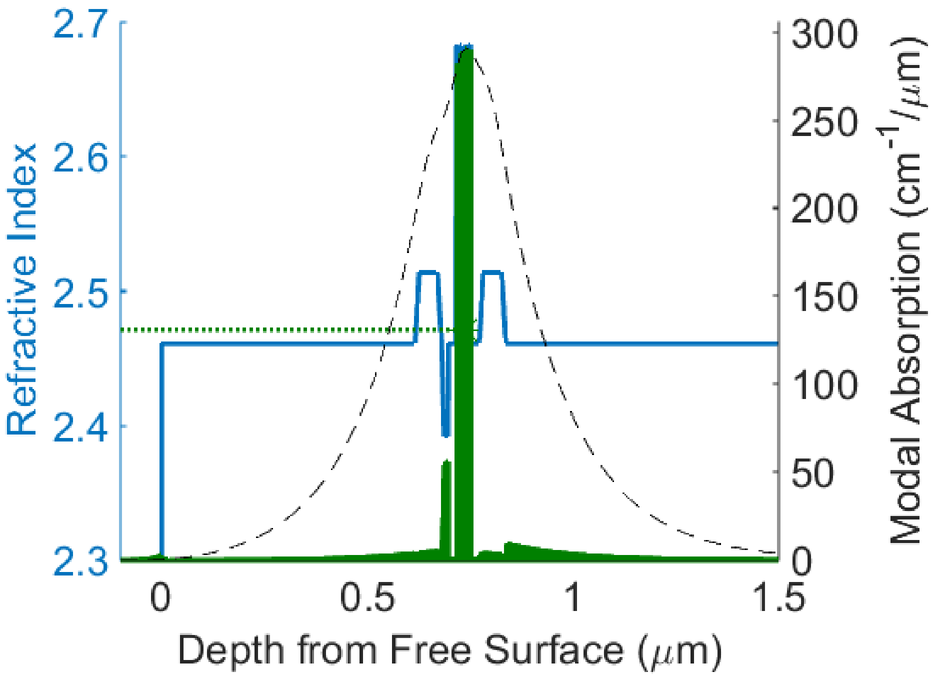
$\langle \alpha_i \rangle$	10 cm^{-1} ± 2 cm^{-1}
η_i	0.80 ± 0.1

Previous measurement on Violet Lasers on m-plane at UCSB:
<α_i> =9.8cm^{-1} **η_i** =66%



Simulation of Confinement & Loss

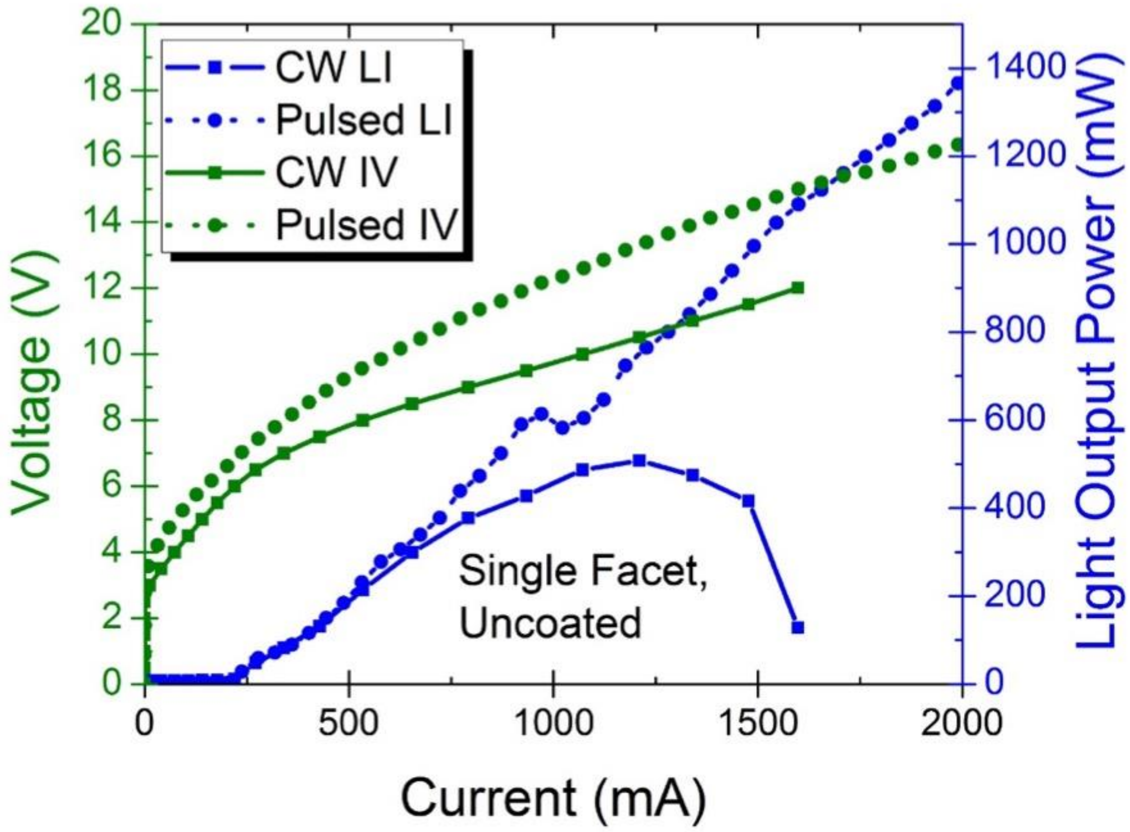
Layer	Loss %
p-metal	1.0%
p-clad	7.7%
p-SCH	4.0%
EBL	9.5%
subtotal: p-top	**22.3%**
QW	52.6%
subtotal: active region	**53.3%**
n-SCH	3.1%
n-clad	19.6%
subtotal: n-bottom	**24.4%**



Effective Index	**Confinement Factor**	**Calculated $\langle \alpha_i \rangle$**	**Experimental $\langle \alpha_i \rangle$**
2.47	0.36	7.65 cm^{-1}	10 cm^{-1} ± 2 cm^{-1}

2 QW Laser

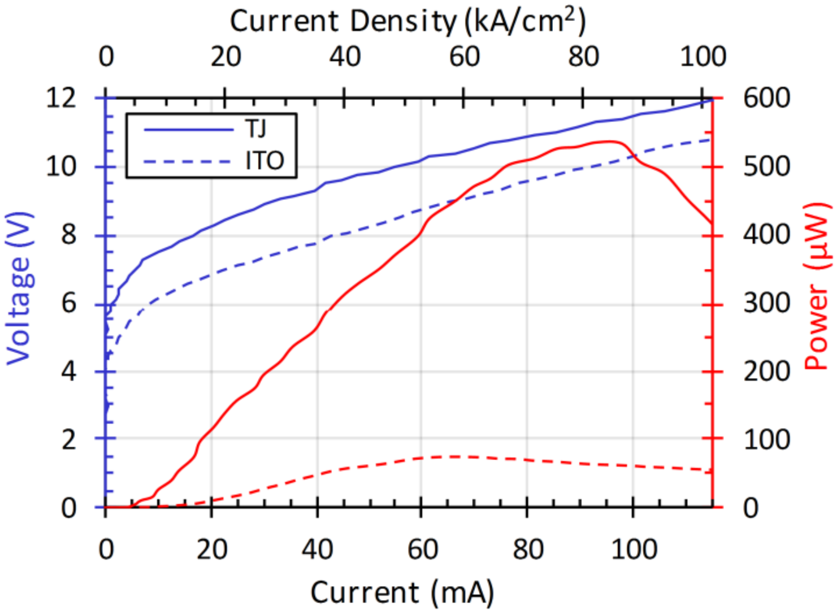
1200 μm x 5 μm LD λ=428nm
Single facet, uncoated



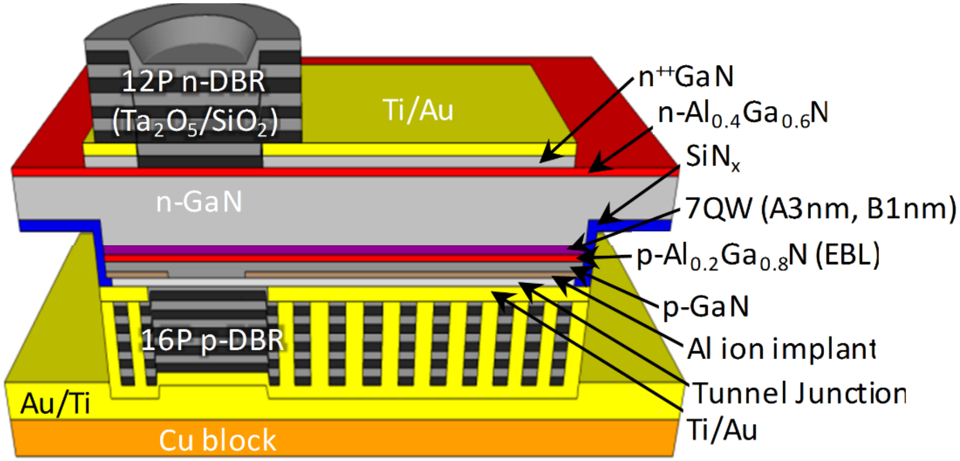
	CW	Pulsed (0.5% duty cycle)
Rd (Ohms)	3.6	4.1
Ith (mA)	214	231
Jth (kA/cm^2)	3.6	3.8
Vth (V)	5.9	7.0
Slope Eff. (W/A)	0.67	0.78
Diff. Eff.	23%	27%
2 facet Slope Eff.	**1.34**	**1.56**
2 facet Diff. Eff.	**46%**	**54%**

Becerra et al. Appl. Phys. Expr. **9**, 092104 (2016).

InGaN m-plain VCSEL with tunnel junction intracavity contact



Leonard, J. T. *et al. Appl. Phys. Lett.* **107,** 091105 (2015).



Leonard, J. T. *et al. Appl. Phys. Lett.* **107,** 011102 (2015).

Loss in ITO - 30 cm^{-1}

Loss in Tunnel Junction - 3 cm^{-1}

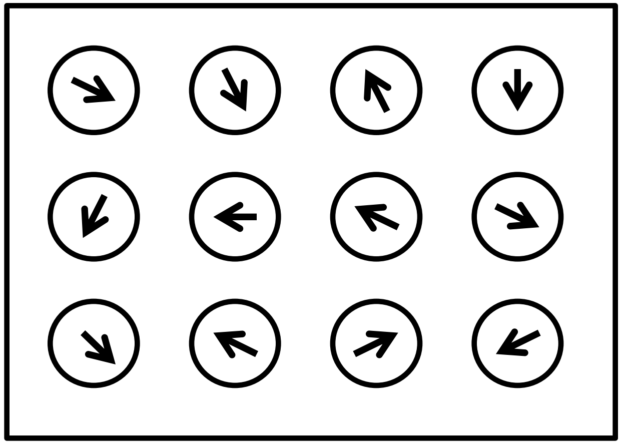
10 times less loss for tunnel junction (TJ) contact layer compared with ITO

7x enhancement in peak power with TJ

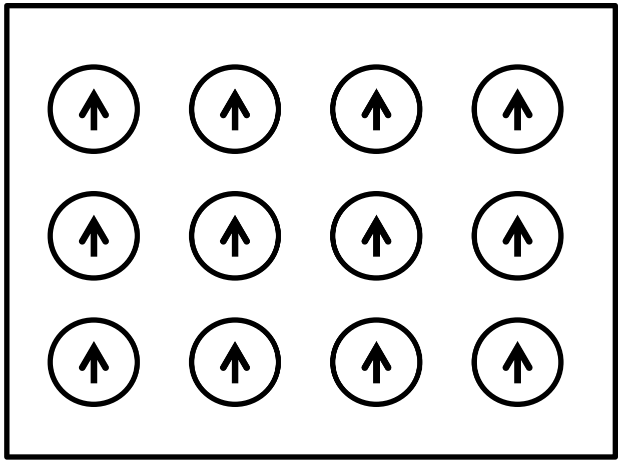
Leonard, J. T., Young, E. C., Yonkee, B. P., Cohen, D. a., Margalith, T., DenBaars, S. P., Speck, J. S.., Nakamura, S., “Demonstration of a III-nitride vertical-cavity surface-emitting laser with a III-nitride tunnel junction intracavity contact,” Appl. Phys. Lett. **107**(9), 091105 (2015). B

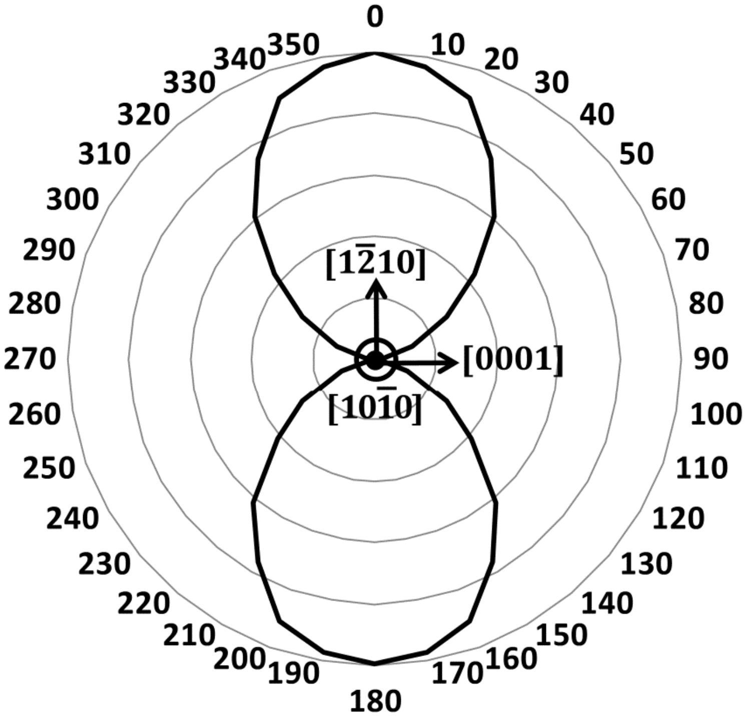
VCSEL Results – Polarization

Conventional VCSEL Array



Nonpolar VCSEL Array





Normalized Intensity vs. Polarizer Angle

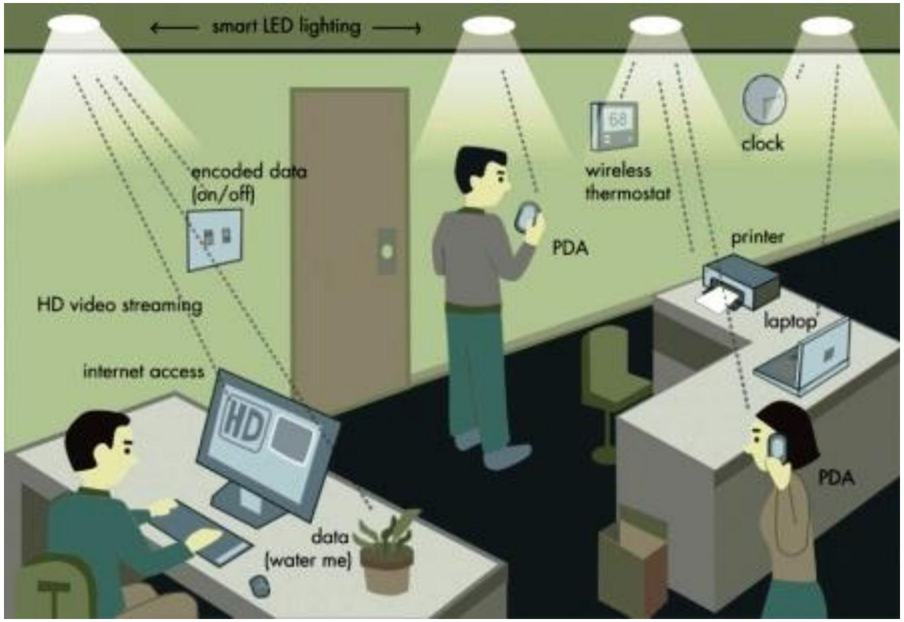
Fiber-Coupled Measurement

Polarization Ratio = 100%!

Laser Lighting

Li-Fi with LEDs and LDs

Intelligent LED Light and Communication Systems



Source:www.electronicsbus.com

NETWORKING future tech, wi-fi

'LiFi' uses LEDs for blazing fast data transfer

Nick Barber
@nickjb

Nov 7, 2013 4:45 AM

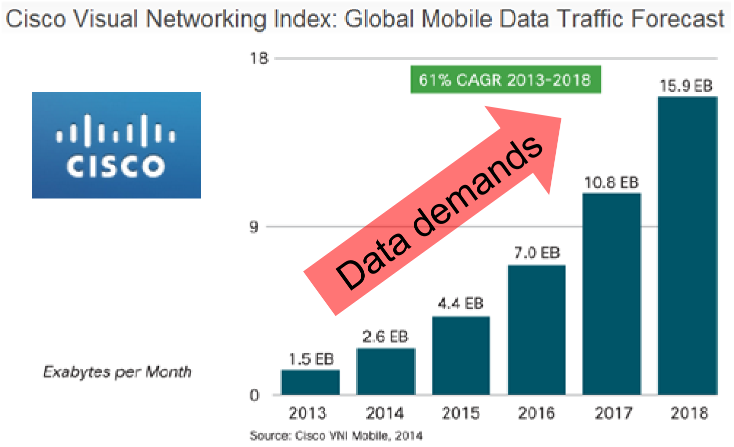
A new technology called LiFi can transfer data using LED lights. In this video, we'll watch a demo of a LiFi system made with off-the-shelf-parts, as it streams a vide.

- Li-Fi communication network
- Sensor, Alarm System, Social Preference
- Higher capacity than Wi-Fi.

Data Rate: LED Li-Fi>10xWi-Fi, Laser Li-Fi > 100~1000xWi-Fi

Motivation

- RF spectrum crisis
  - Mobile data demands are exponentially increasing but spectrum efficiency is saturated
- Advantages of VLC
  - ~hundereds THz of unlicensed spectrum available
  - No EM interference (EMI)
  - High security
  - Cost-efficient


Cisco Visual Networking Index: Global Mobile Data Traffic Forecast

Source: Cisco VNI Mobile, 2014

Motivation

- RF spectrum crisis
  - Mobile data demands are exponentially increasing but spectrum efficiency is saturated
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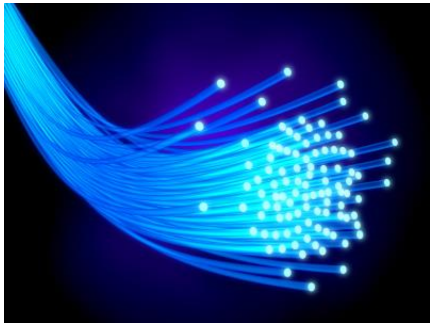
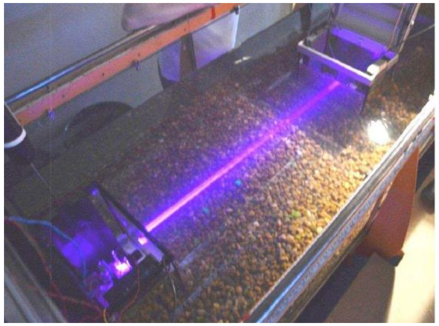
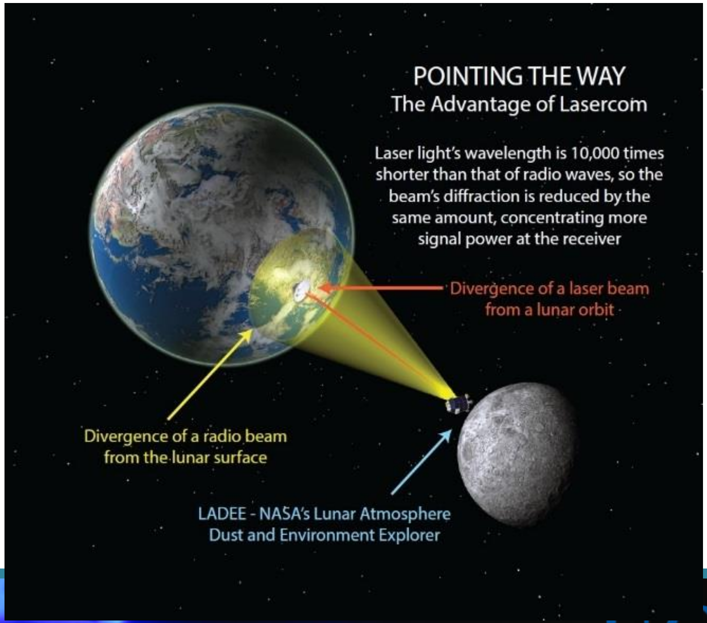


Plastic fiber optics



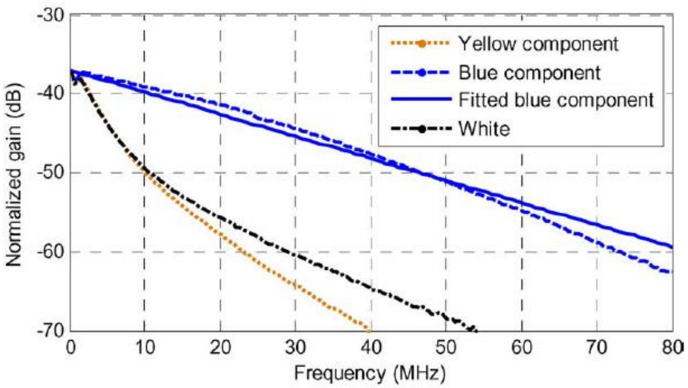
Underwater communication



Satellite-to-satellite communication

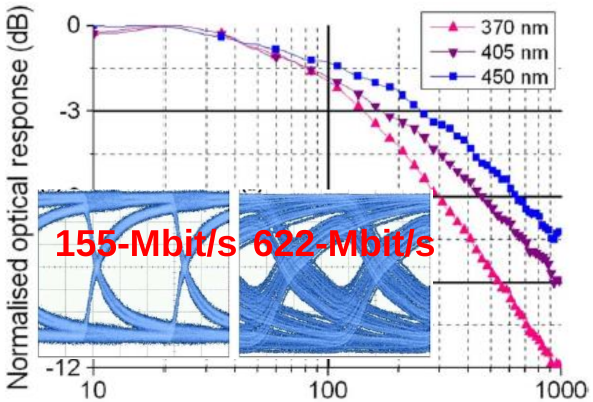
Bandwidth limits in VLC transmitter

Commercial LED



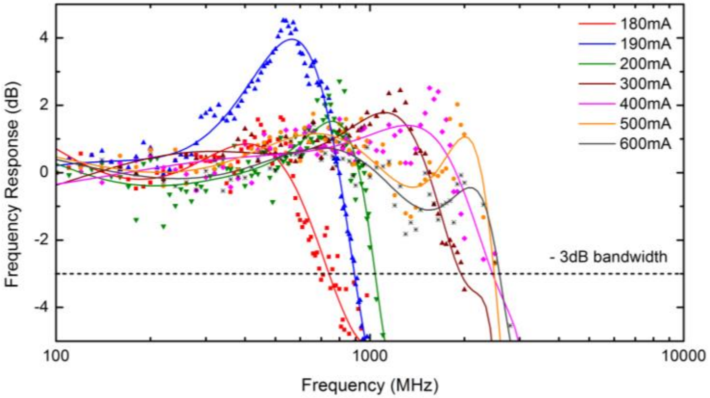
BW of ~ 20 MHz, 100 Mbps OOK

Single micro-LED



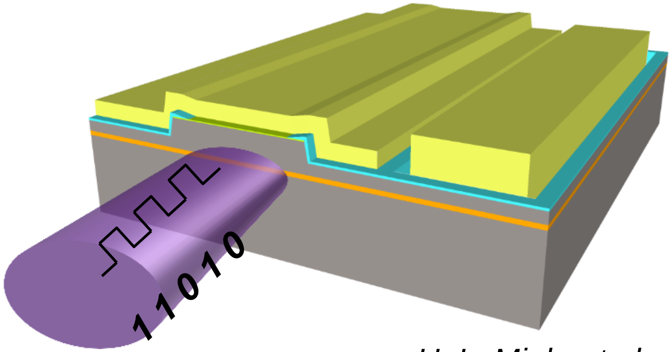
BW of 200 ~ 800 MHz, 1.7 Gbps OOK

Commercial LD



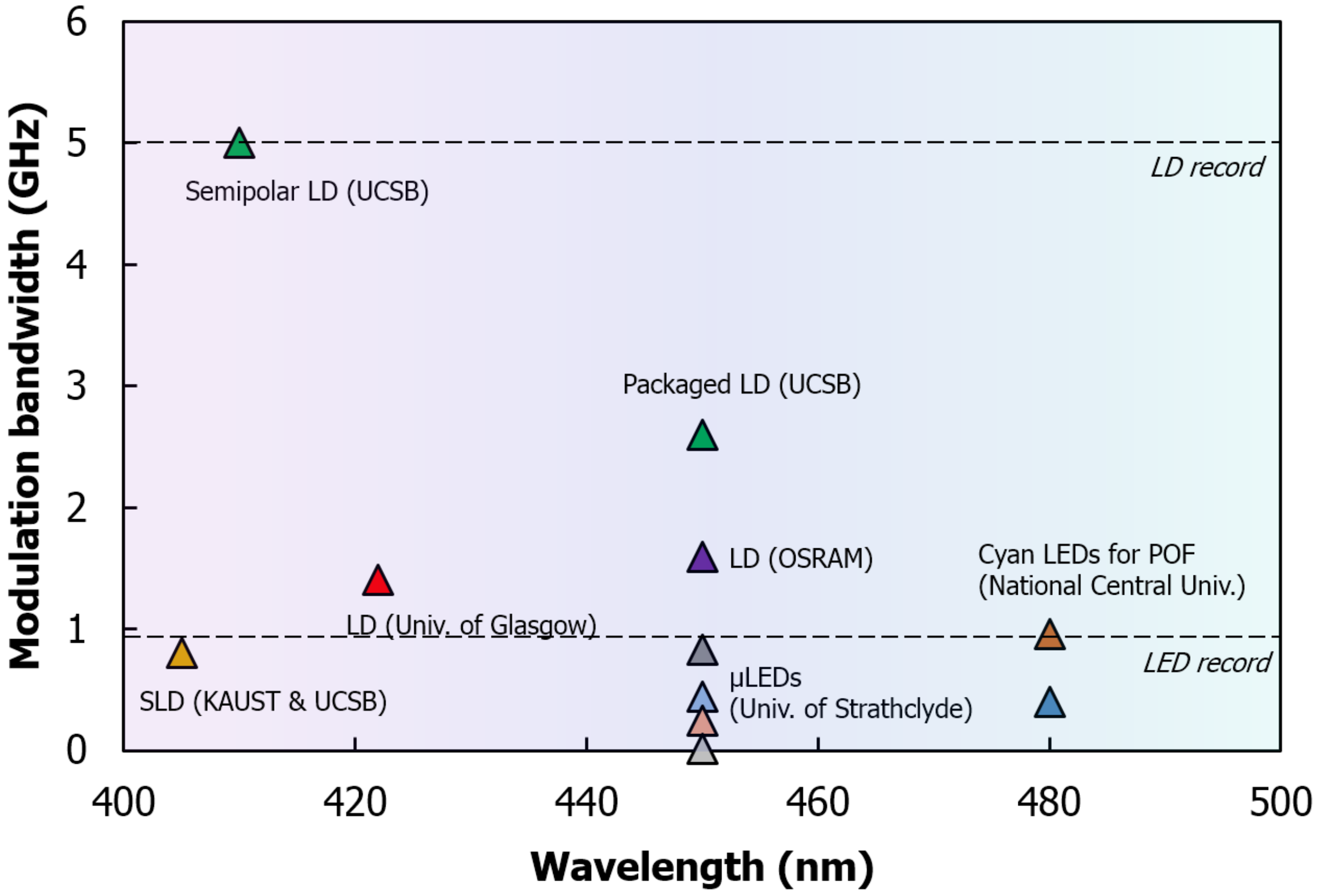
BW of > 2 GHz, 4 Gbps OOK

Higher speed LD?



H. L. Minh, et al., IEEE PTL, 2009
J. J. D. McKendry, et al., IEEE PTL, 2010
C. Lee, et al., Opt. Express, 2015

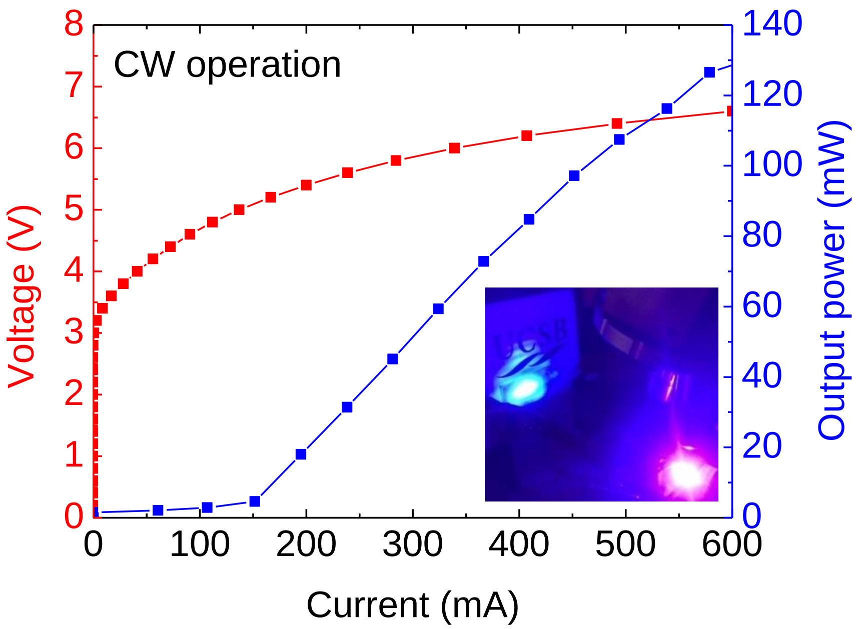
Records in III-nitride LDs and LEDs



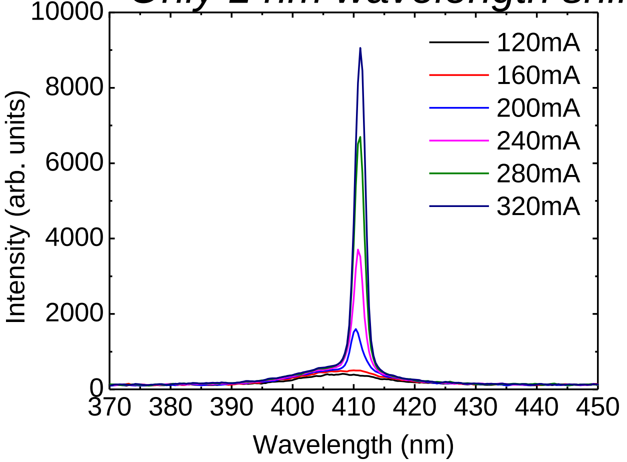
BW_{max} of LEDs: 1 GHz (carrier lifetime limit)
BW_{max} of LDs: 5 GHz (photodetector bandwidth limit)

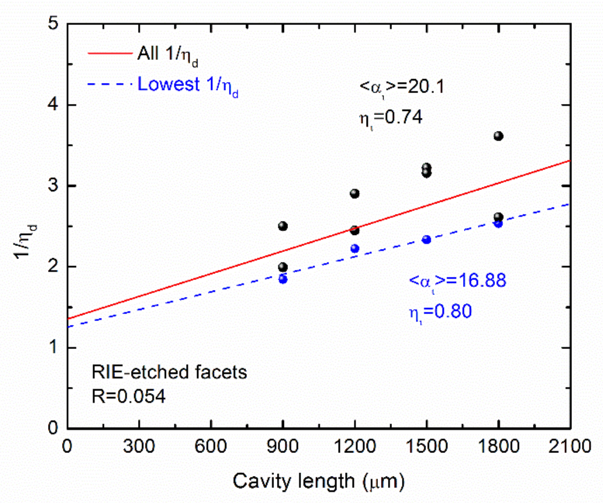
Semipolar (20-2-1) Laser Diode

Violet CW LD on (20-2-1) plane (2 µm x 1200 µm)



Only 1 nm wavelength shift





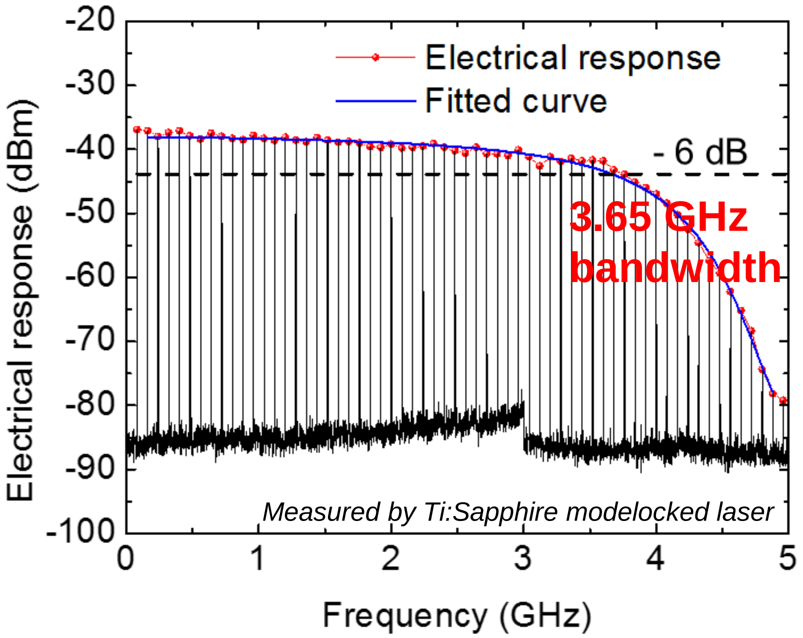
C. Lee, et al., Appl. Phys. Lett., 2016

CW data	I_{th} (mA)	J_{th} (kA/cm2)	V_{th} (V)	*dP/dI* (W/A)
2µm x 1200µm	150	6.25	5.1 (4-pt)	0.35

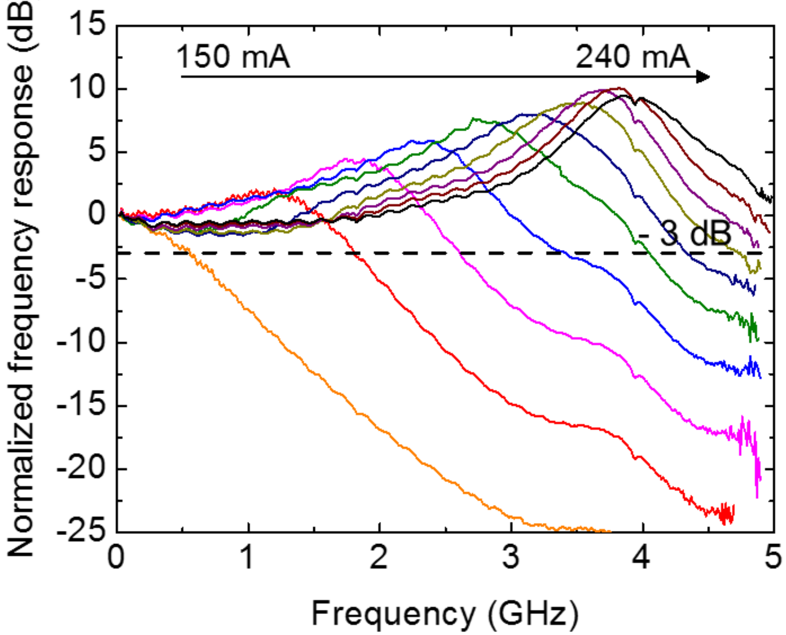
Injection efficiency have good agreement with semipolar blue LD by D. Becerra et al., Appl. Phys. Express, 2016

Modulation bandwidth

PD response



Recovered LD response



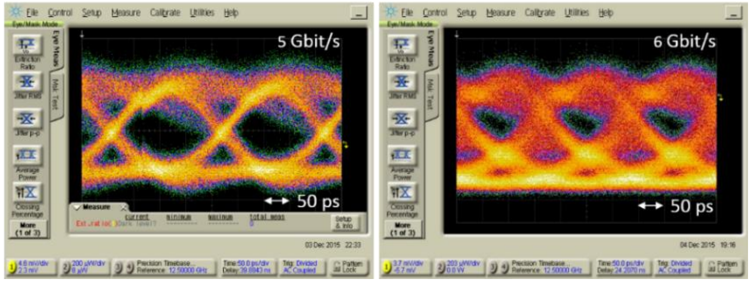
After correcting PD response:

Record BW > 5 GHz due to the noise floor

5 Gbit/s OOK with clear open eyes

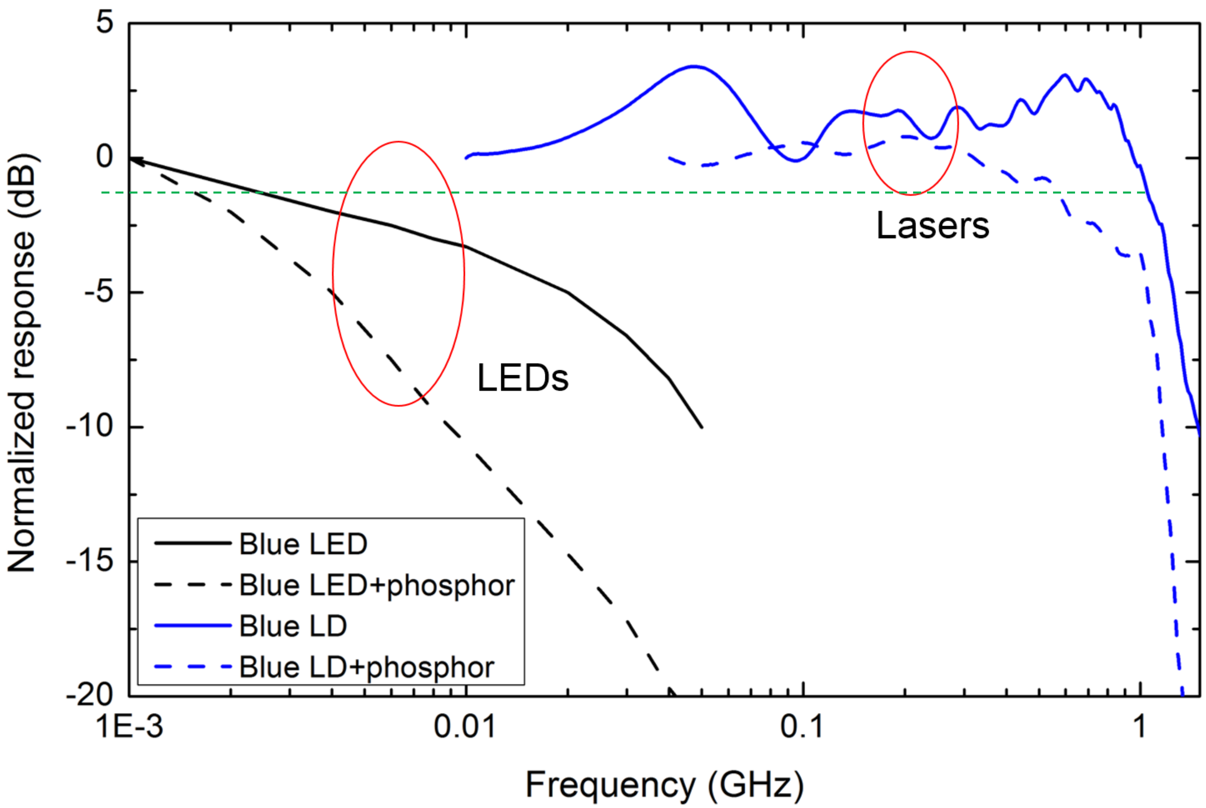
(Higher data rate could be achieved by high speed PD and higher order modulation)

On-off keying (OOK) modulation



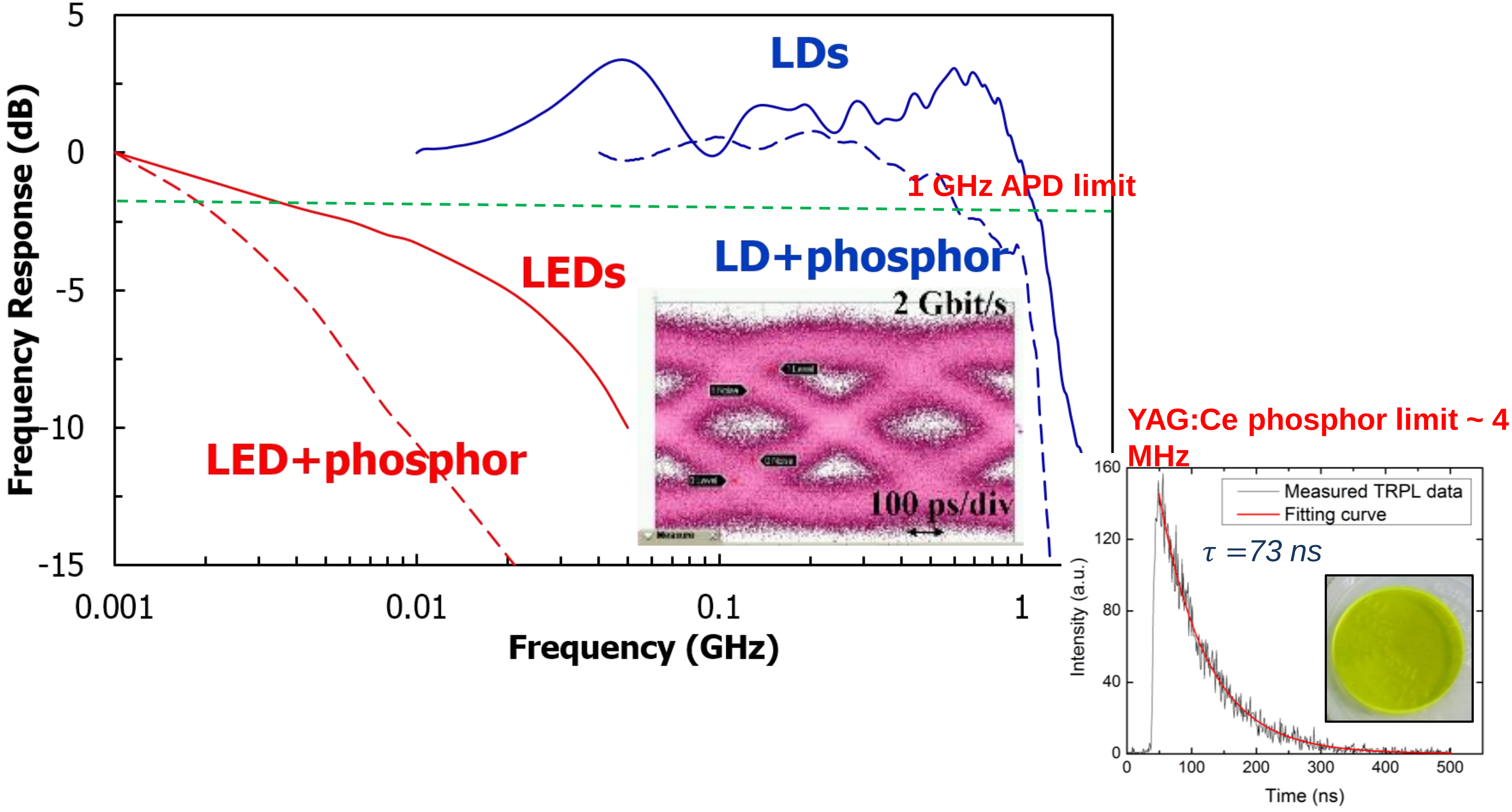
C. Lee, et al., Appl. Phys. Lett., 2016

LDs for LiFi Applications



- LEDs – 14 MHz without phosphor and 2.5 MHz with phosphor
- LDs – 1.2 GHz without phosphor and 1.1 GHz with phosphor (limited by photodetector)
- **LDs are ~1,000 times faster than LEDs for white lighting data transmission**

White LED vs. LD VLC



1 GHz APD limit

YAG:Ce phosphor limit ~ 4 MHz

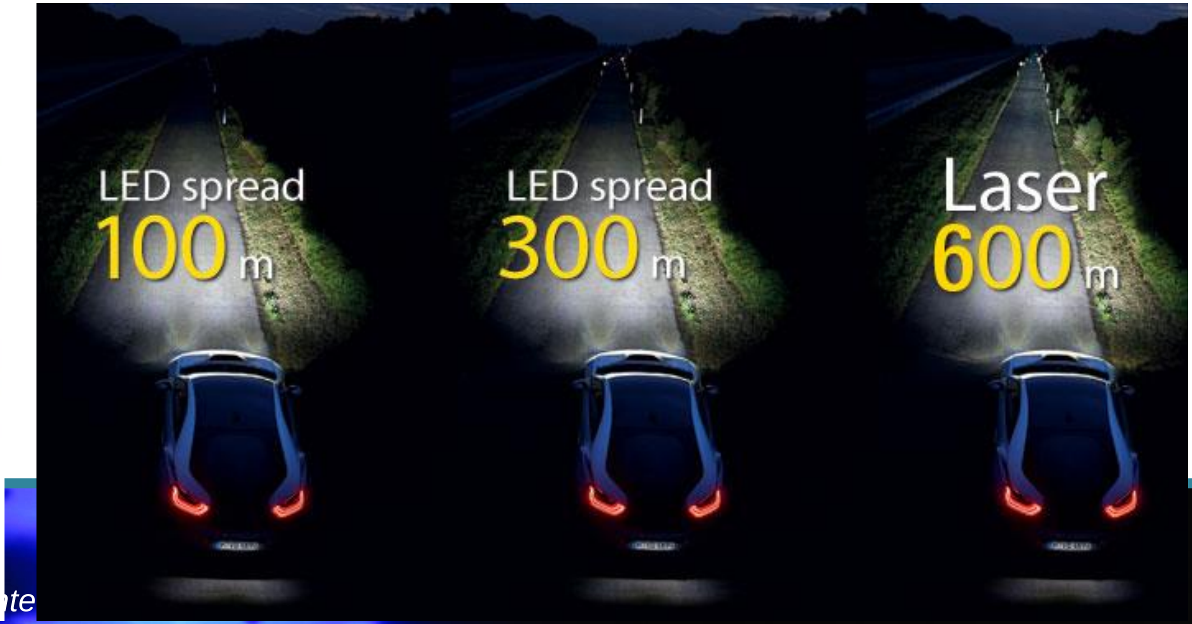
C. Lee, et al., Opt. Express, 2015

Laser Diodes – Light of the Future

Laser Headlights

Laser Projectors

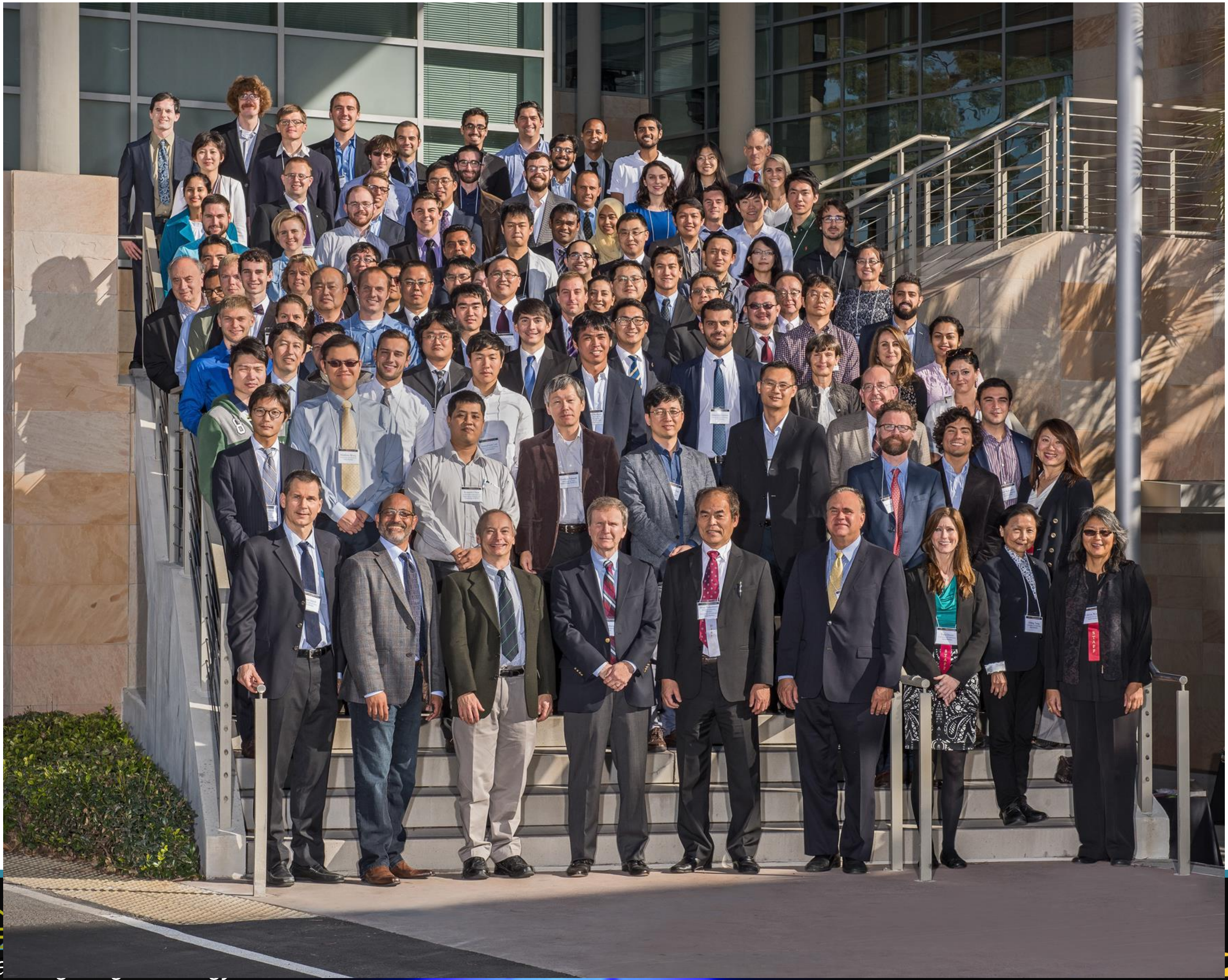
100 inch TV



BMW with Laser Lighting Headlights

BMW with laser headlights
(available in US!)

Researchers at UCSB: SSLEEC in 2016



thanks !

Photo by Tony Mastres