The Invention of High Efficient Blue LED and Future Solid State Lighting

Prof. Shuji Nakamura

Co-founder of Soraa
Materials and ECE Departments
University of California Santa Barbara

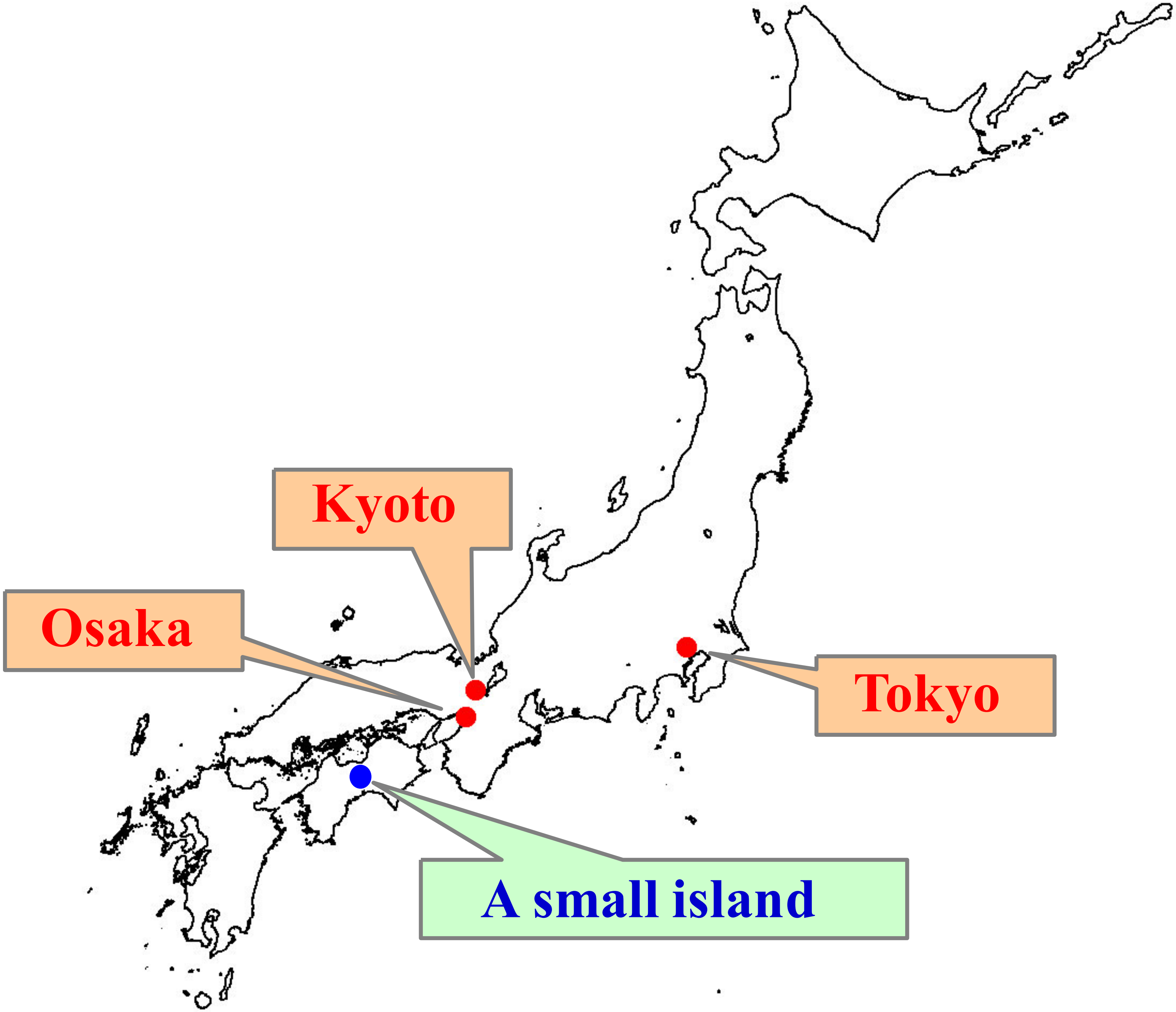
Outline

Introduction

White LED

- *Blue LED on sapphire substrate*
- *Violet LED on GaN substrate by Soraa Inc*

Laser Lighting


Kyoto
Osaka
Tokyo
A small island


Tokushima
Anan
Ozu city (Elementary ～high school
A small island
Ohku
SB

I joined Nichia in 1979 after graduation of University of Tokushima

Message by President of Science Council of Japan

On behalf of the academic community of Japan, congratulate for winning the Nobel prize.

Professors Akasaki and Amano developed the first blue LED in 1989.

Profess Nakamura developed the manufacturing technology of the blue LED in 1993.

Introduction of three noble prize laureates in japan

After Noble prize announcement, all of the Japanese media, TV, newspapers and academic people have introduced about three noble prize laureates (industry, government and academic people together)

1) Professors Akasaki&Amano: Developments of blue LED in 1989

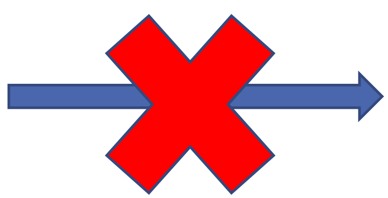
2) Professor Nakamura: Developments of manufacturing technology in 1993

Alfred Nobel's Will

The Establishment of the Nobel Prize

"The whole of my remaining realizable estate shall be dealt with in the following way: the capital, invested in safe securities by my executors, shall constitute a fund, the interest on which shall be annually distributed in the form of prizes to *those who, during the preceding year, shall have conferred the greatest benefit on mankind*. The said interest shall be divided into five equal parts, which shall be apportioned as follows: *one part to the person who shall have made the most important discovery or invention within the field of physics*;

Developments of manufacturing technology

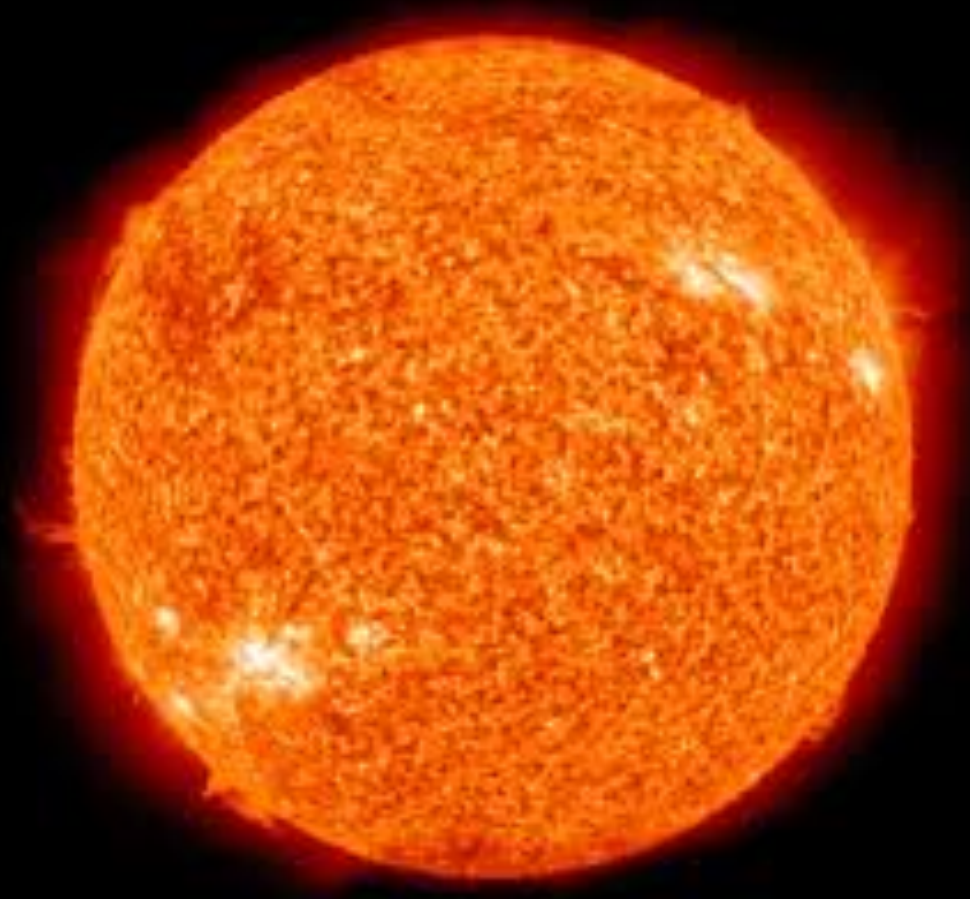


Noble prize in Physics

What is an LED?

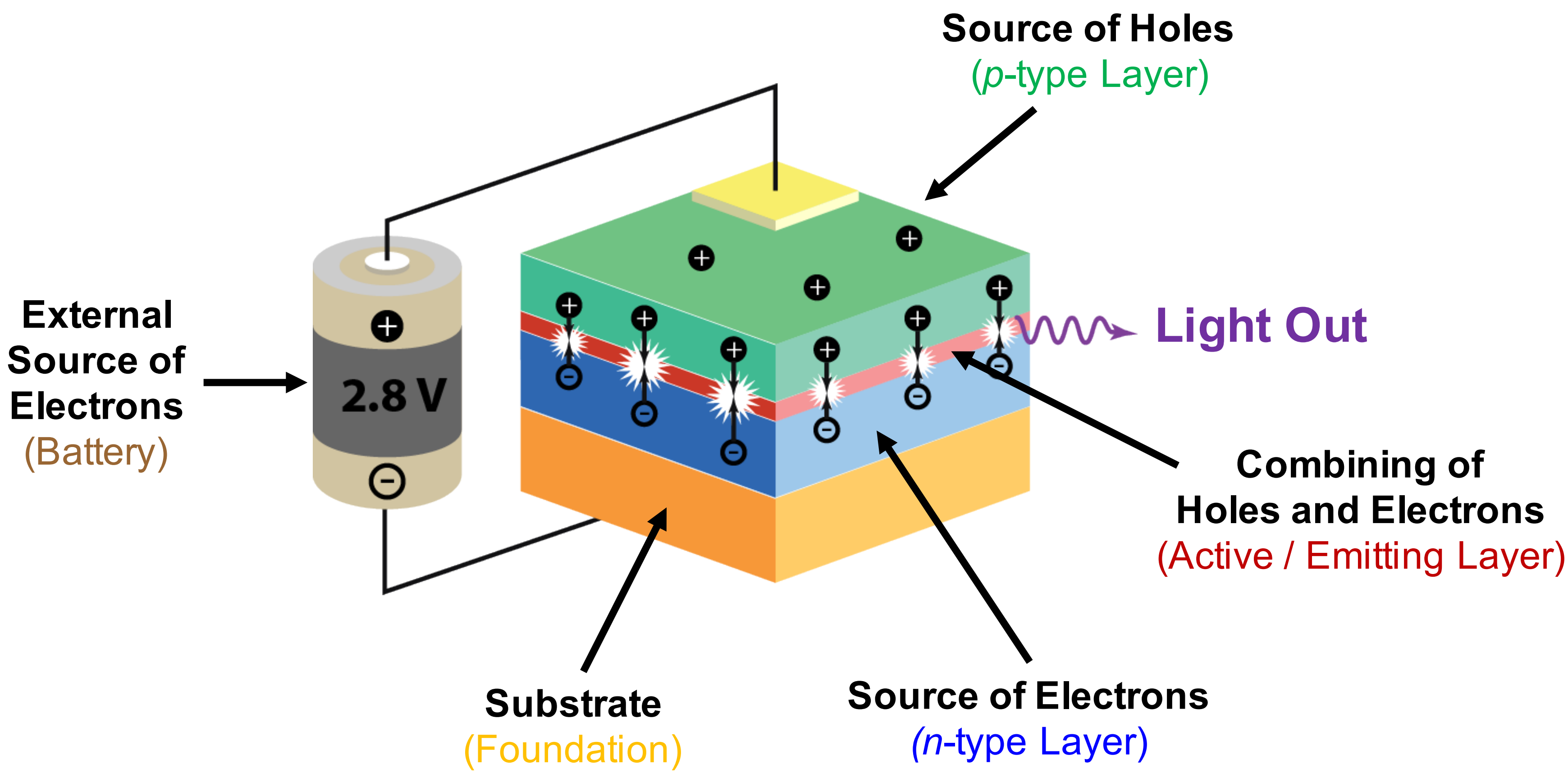
ENERGY EFFICIENT WHITE LIGHT

First Source of Light for Life: Our Sun



What is an LED?

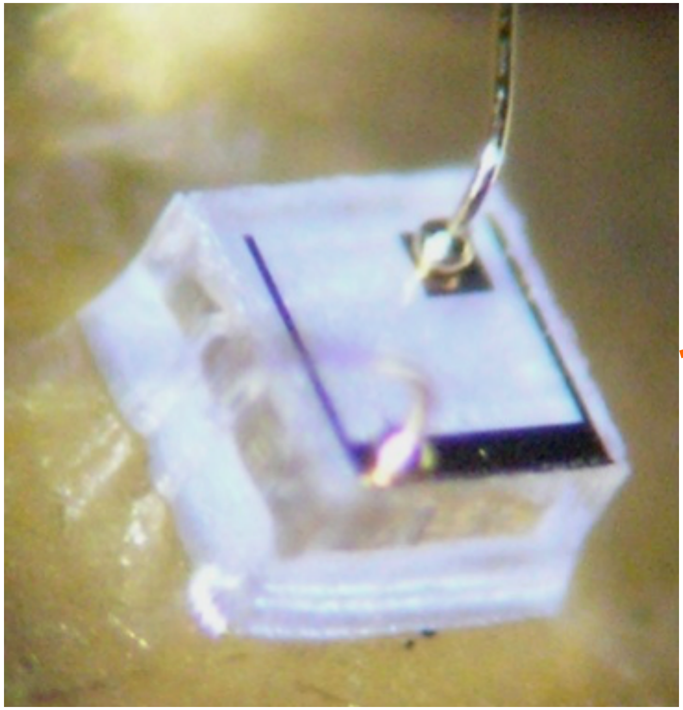
A Light Emitting Diode (LED) produces light of a single color by combining holes and electrons in a semiconductor.



What is an LED?

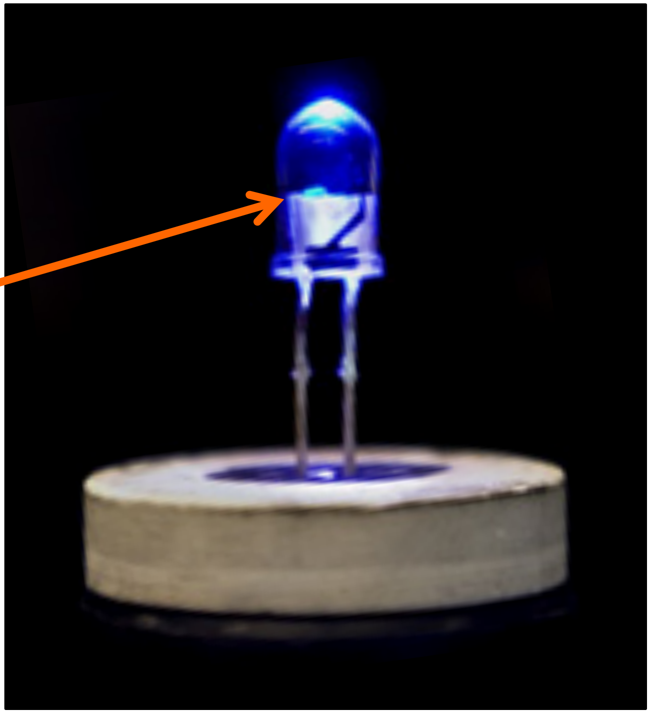
A Light Emitting Diode (LED) produces light of a single color by combining holes and electrons in a semiconductor.

Actual Blue LED

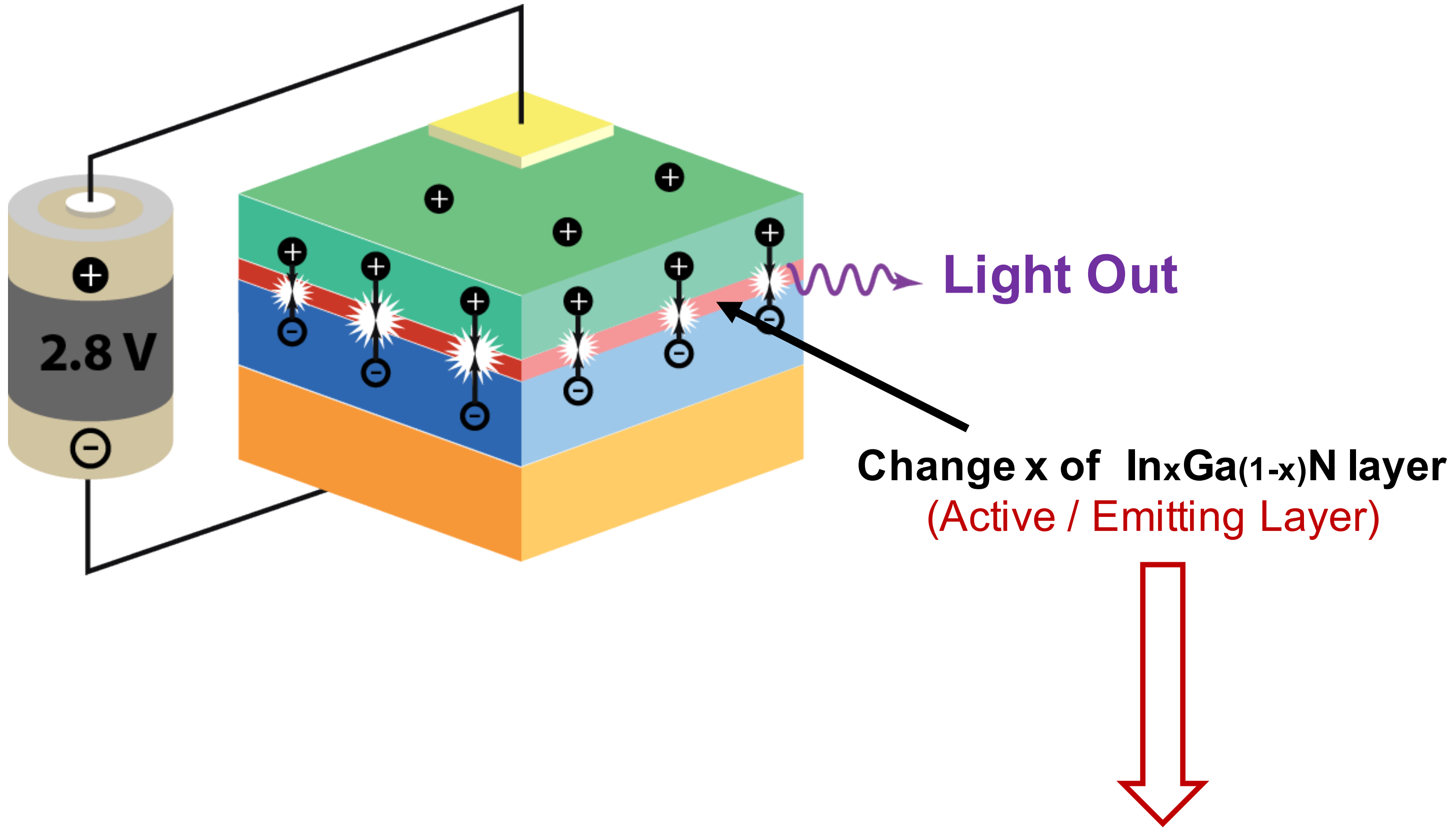


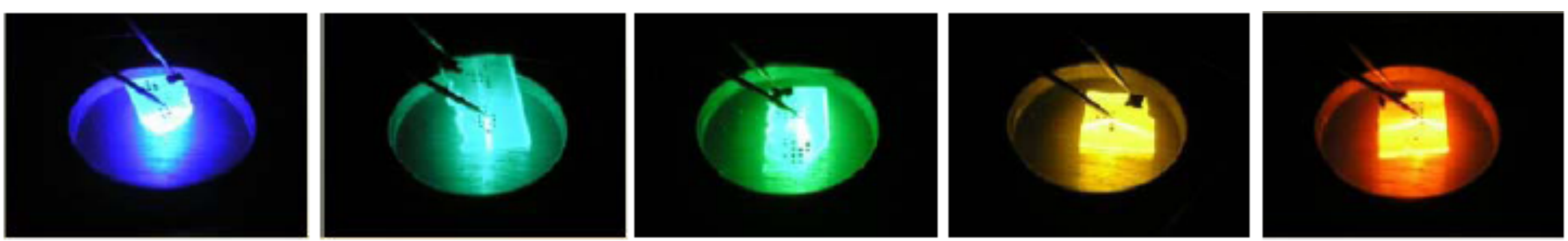
Size: 0.4 mm x 0.4 mm

Packaged Blue LED



Different Colors Possible!

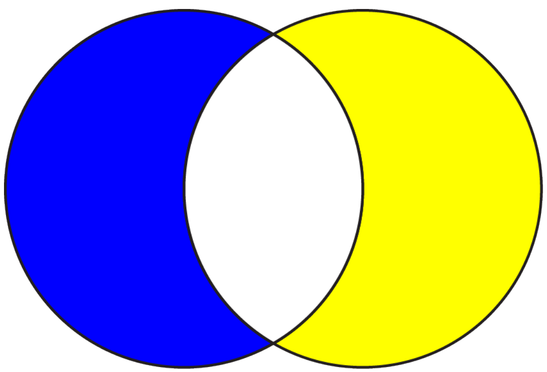




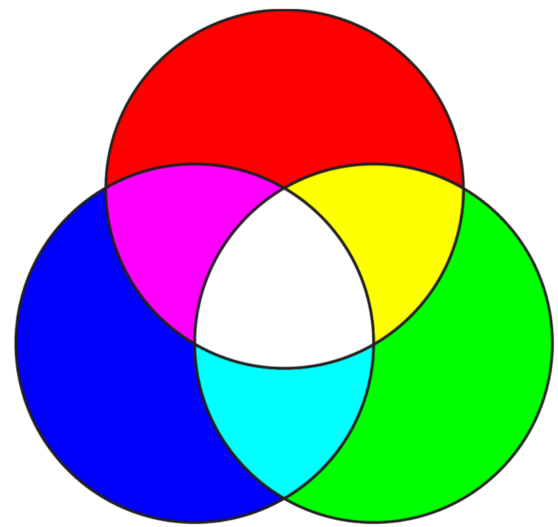
Combining Colors

One LED can only produce **one color**
(red, orange, yellow, green, blue, or violet)

To achieve white light, need to **combine colors**:



Blue + Yellow
(Easiest)



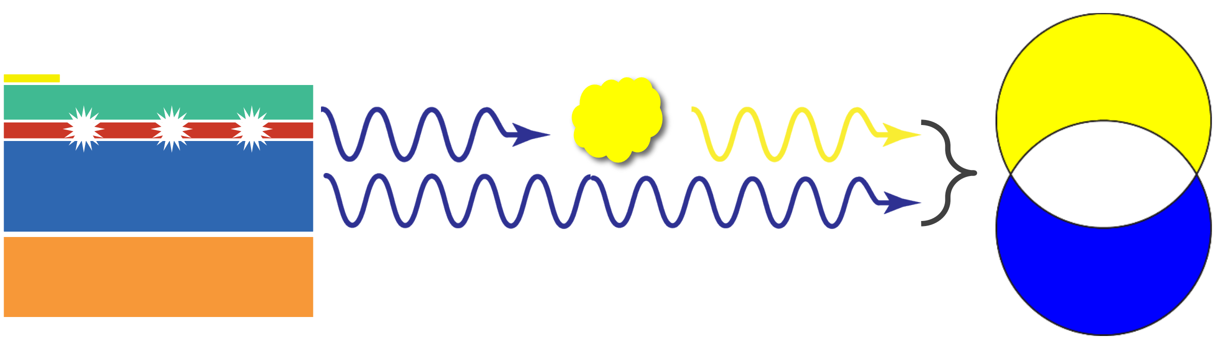
Blue + Green + Red
(Highest Quality)

White LED: Combining Colors

White Light: Blue + Other colors (red, yellow, green)

Other Colors: Convert Blue LED Light to Yellow using Phosphor.

Blue LED	**Phosphor** Convert: Blue → Yellow	**White Light** = Blue + Yellow	**White LED**



S. Pimputkar et al., *Nature Photonics* **3** (2009) 180—182

Conventional White LED (Blue LED + Phosphor)

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

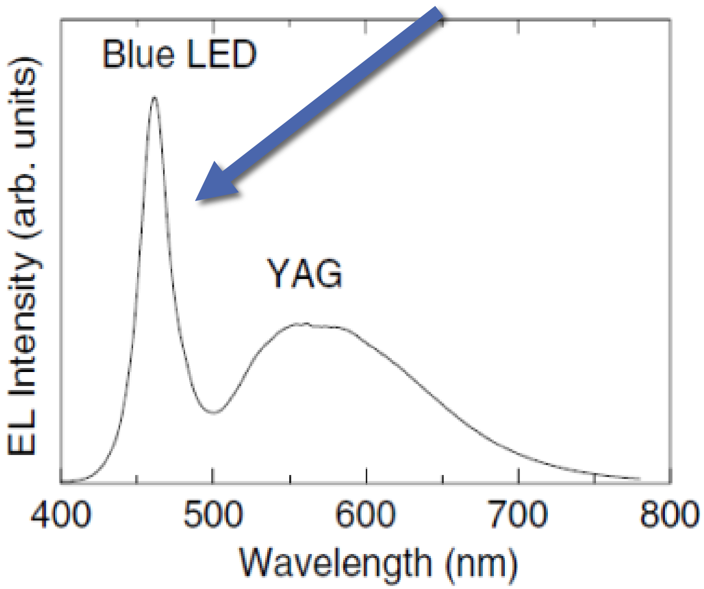


Figure 2. The typical emission spectrum of a white LED using a YAG phosphor at 20 mA. T_{cp} is 6500 K.

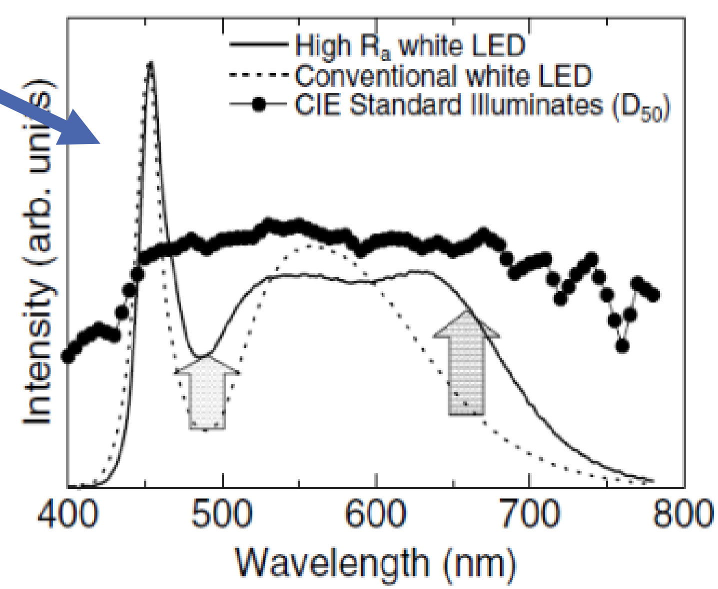


Figure 3. The spectra of the ultra-high R_a white LED, the conventional white LED and CIE Standard Illuminates (D_{50}). All of T_{cp} are 5000 K.

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

Apple move 'acknowledges blue light dangers'

LUX Review January 19, 2016

http://luxreview.com/article/2016/01/apple-move-acknowledges-blue-light-hazard-

Apple move 'acknowledges blue light dangers'

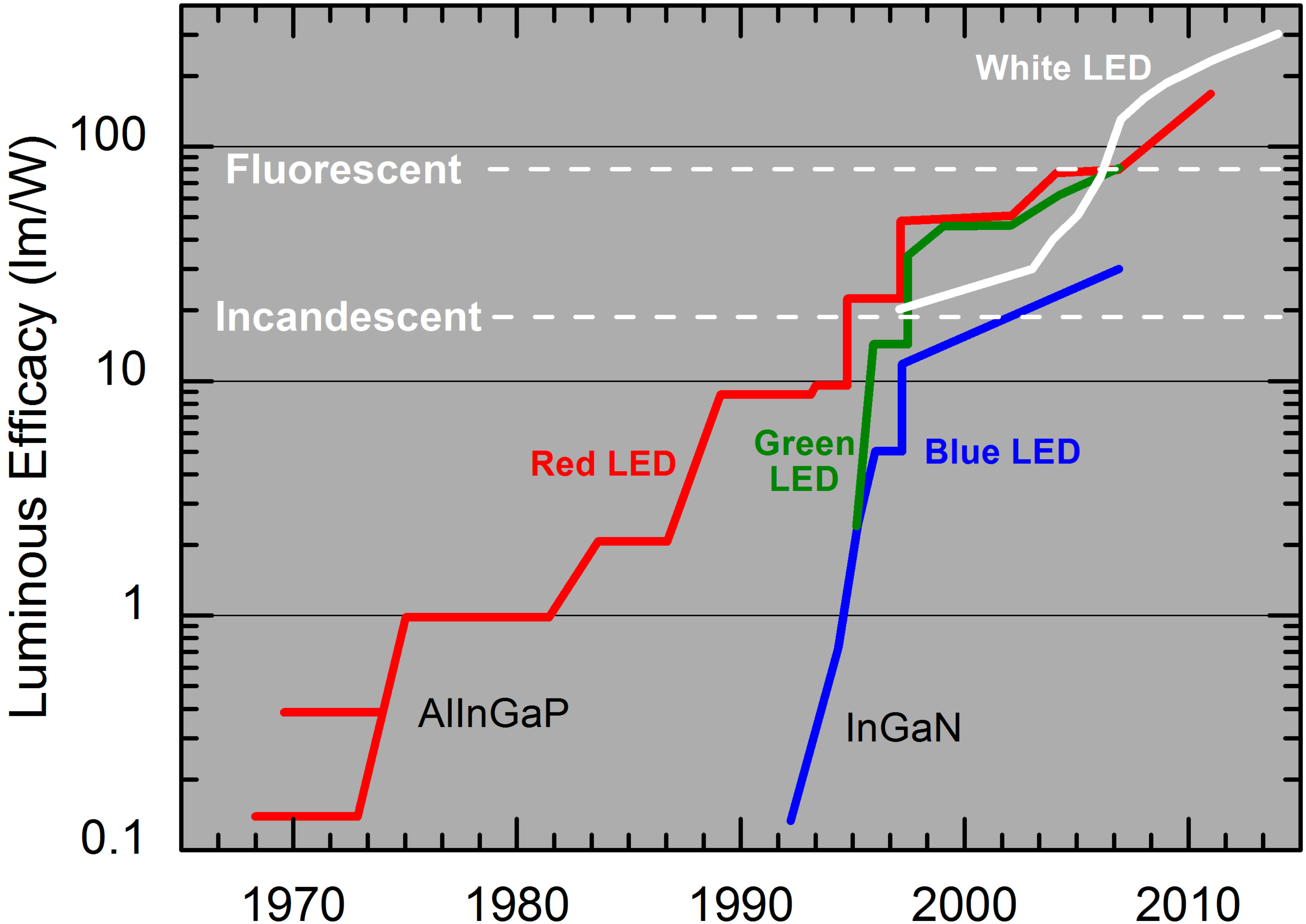
The blue 'spike' in the white light output from an electronic device reduces production of the sleep hormone melatonin, and has been linked to various health disorders including cancer

The White LED

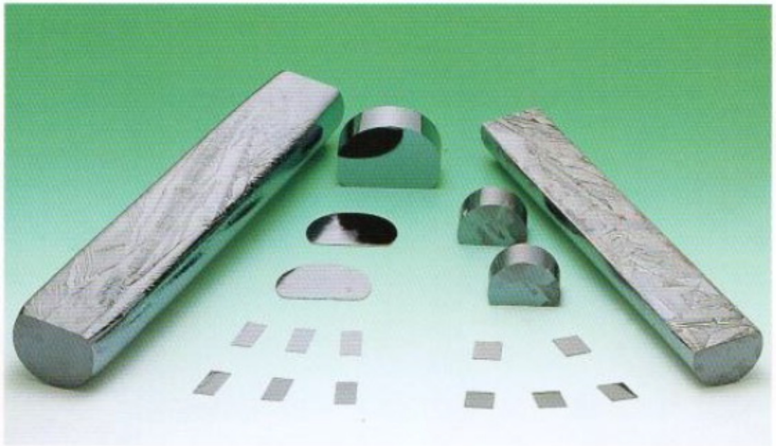
White LED

White LED Bulb

Historical: LED Efficiency

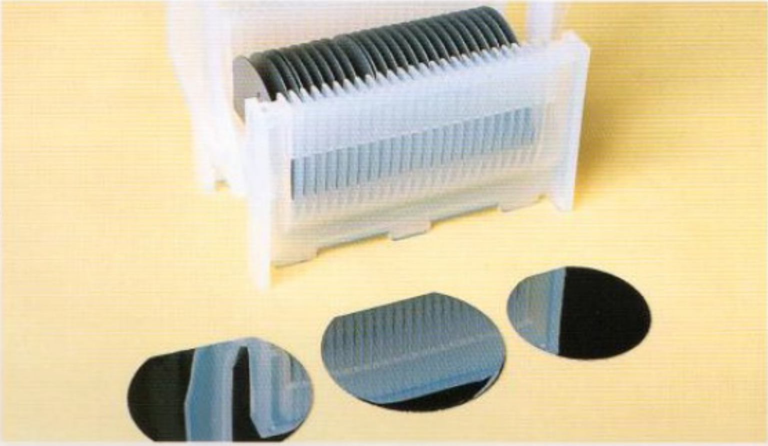


Product Guide of Opto-Electronics from Nichia Corporation Company Profile in 2000



化合物半導体（InP）
Compound Semiconductors(INP)

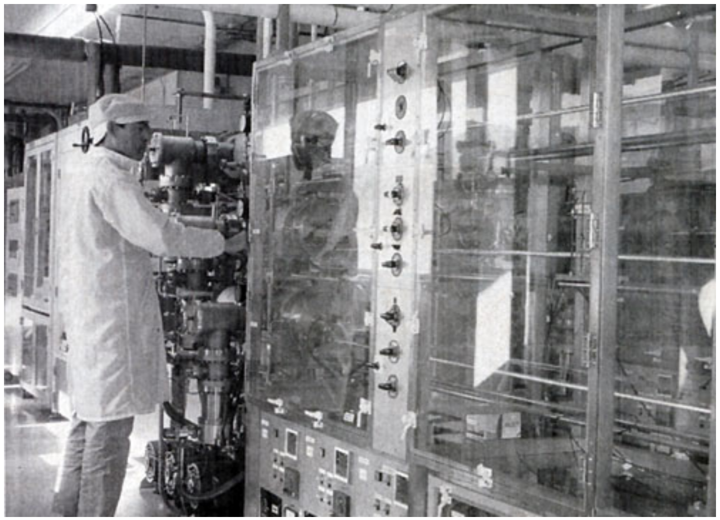
▌単結晶材料
Single Crystal Materials



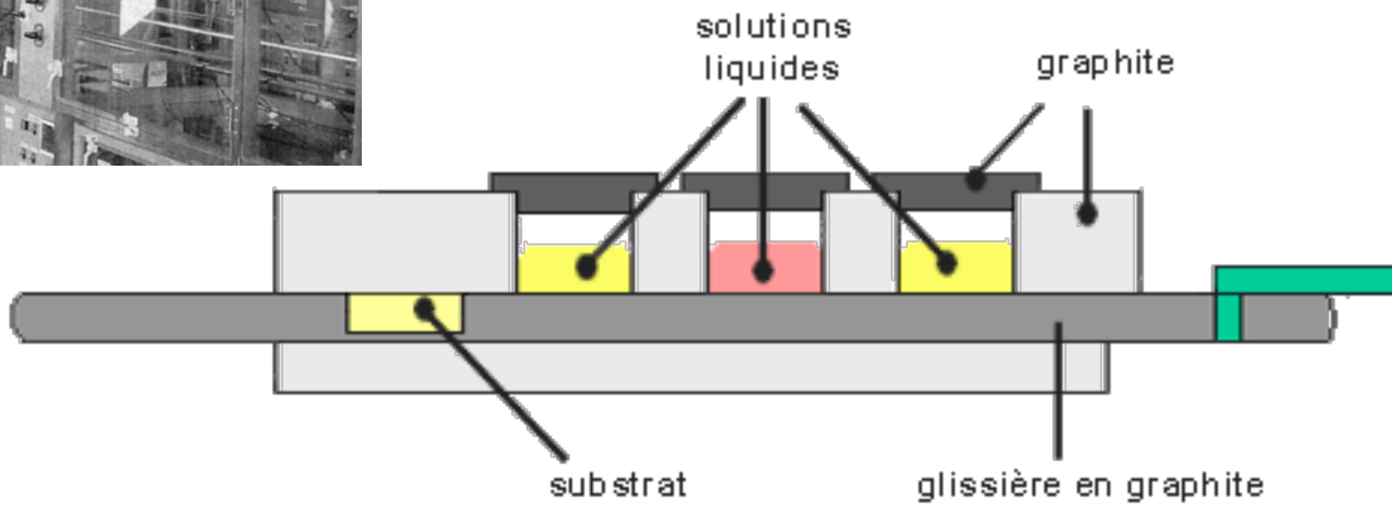
LED赤外エピウエハー
LED Infrared Epitaxial Wafers

▌高出力高速赤外LEDランプ
High-power & High-response Infrared LED Lamps

Liquid Phase Epitaxial Growth of Infrared and Red LEDs from 1985 to 1988



$Al_xGa_{(1-x)}As$



GaAs
Substrate

Impact

SAVING THE WORLD ONE BULB AT A TIME

Applications for InGaN-Based LEDs

Solid State Lighting

Decorative Lighting

Automobile Lighting

Displays

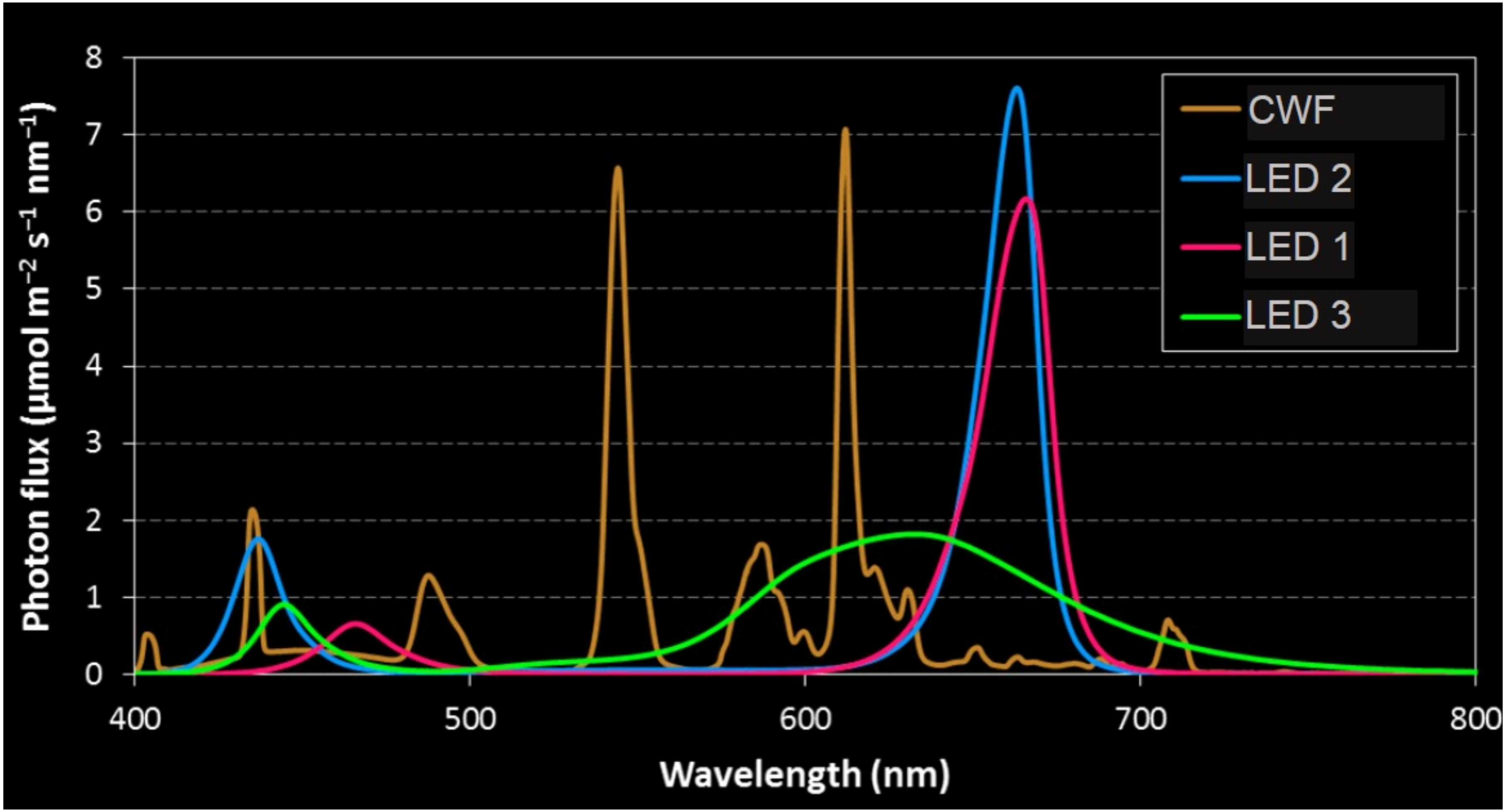
Agriculture

Indoor Lighting

Plant Factory using Blue/Red LEDs in Clean Room

Growth rate is 2.5 times (The latest: 5 times) higher.
Yield of the plant from 50% to 90%
Water usage only 1% compared with outside

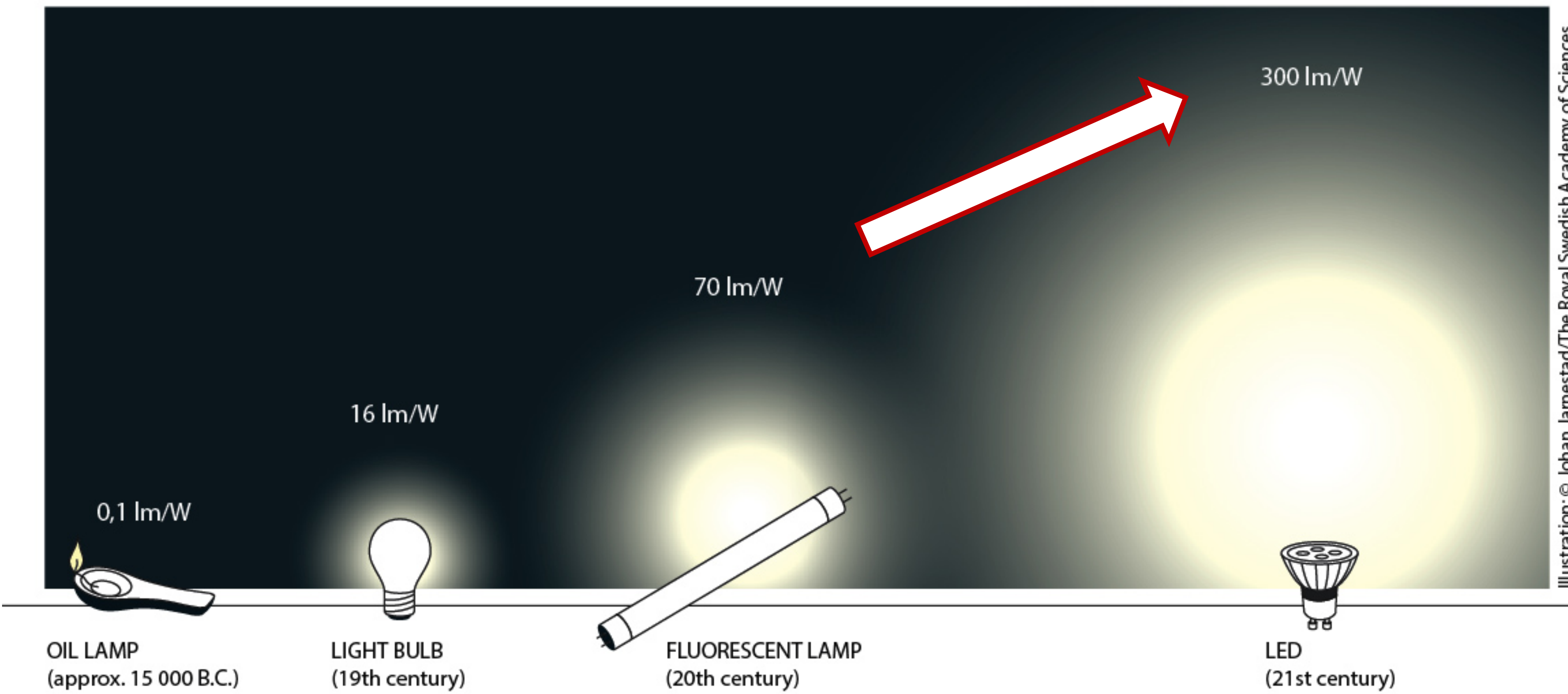
Effect of spectrum on plants (by Dr. Tessa Pocock)



Ocimum Basilicum L.

Energy Savings Impact

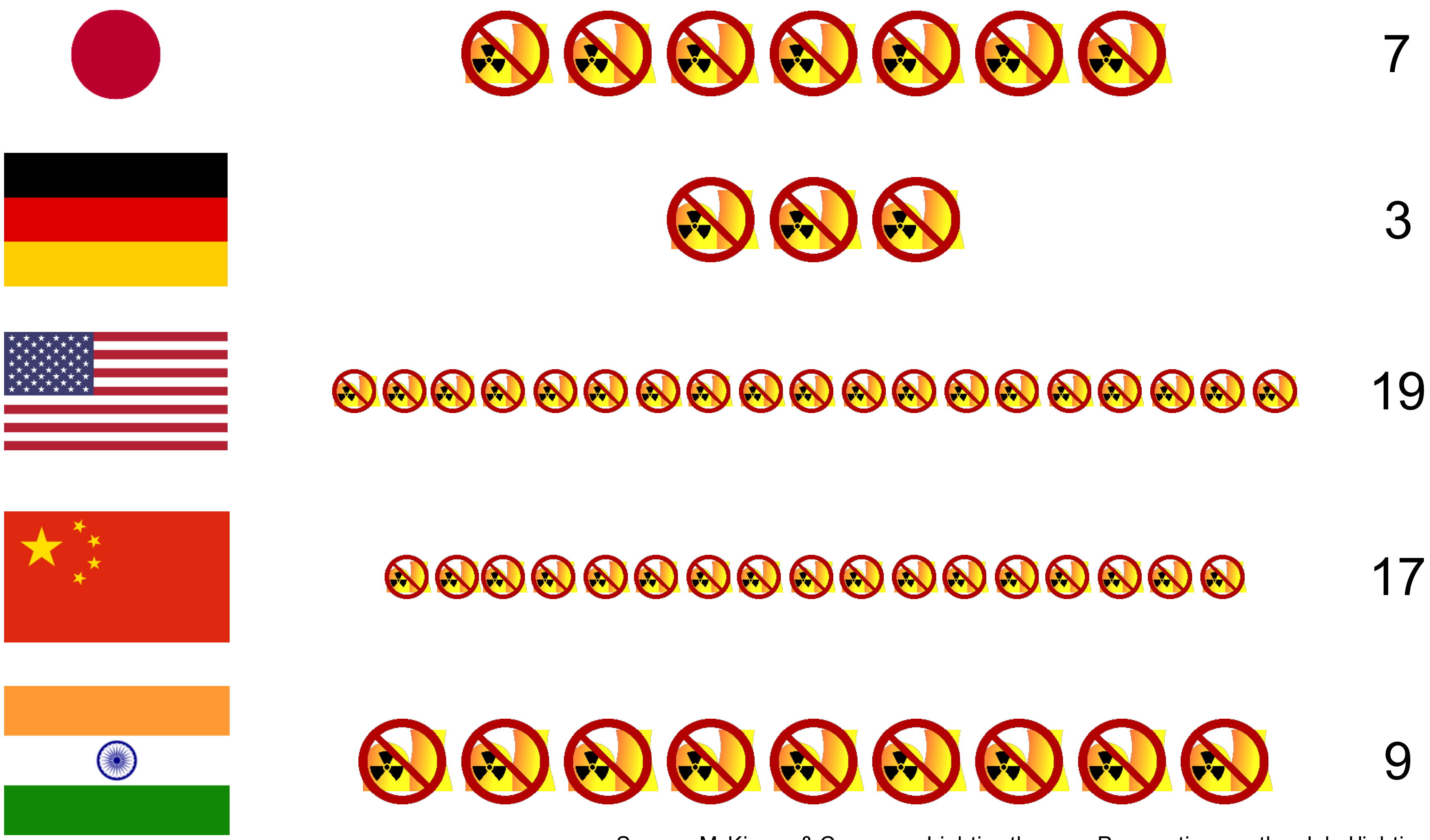
LED efficiency: **4x** fluorescent, **20x** incandescent



Sources: www.nobelprize.org, US Department of Energy

Global Energy Savings due to white LEDs

Redundant Nuclear Power Plants due to LED use by 2020



Source: McKinsey & Company: Lighting the way: Perspectives on the global lighting market

Why was it so hard to make?

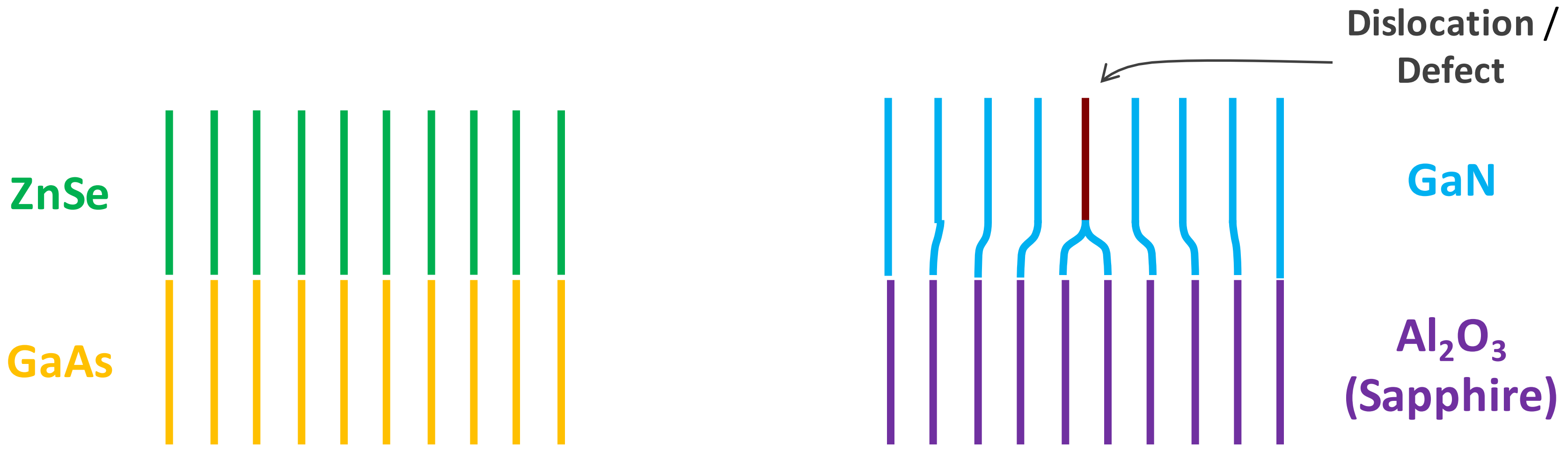
ZnSe vs GaN

Candidates for Blue LEDs: ZnSe vs. GaN

Semiconductors that possess the required properties to *efficiently* generate blue light: **ZnSe** and **GaN**

BUT … How does one ***create*** ZnSe / GaN?

Single crystal growth of material on top of different, available single crystal:



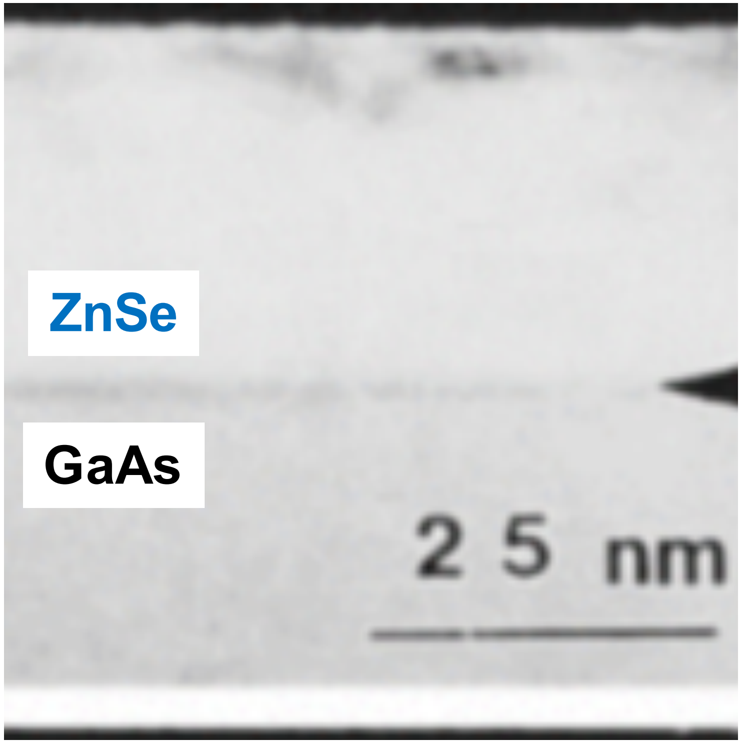
0 % Lattice Mismatch
Few Dislocations (Defects)

16 % Lattice Mismatch
Significant Dislocations (Defects)

Choice of Material in 1980s

For blue LED two choices:

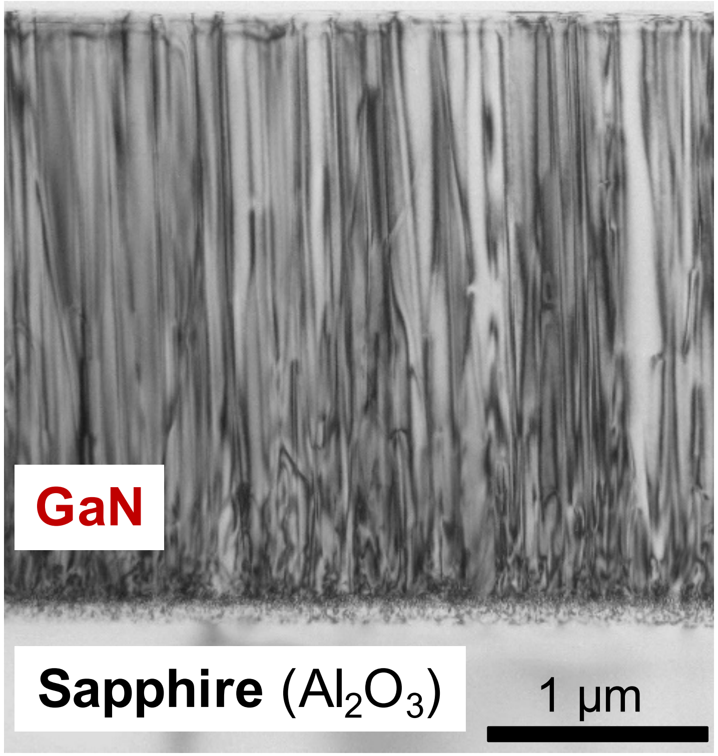
Zinc Selenide (ZnSe)



Cross section TEM (Kuo et al., APL 68 (1996) 2413)

High Quality

Gallium Nitride (GaN)



Cross section TEM of GaN on Sapphire, F. Wu *et al.*, UCSB

Poor Quality

(Black Lines are Defects)

1989: ZnSe vs. GaN for Blue LED

ZnSe on GaAs Substrate

- **High Crystal Quality**: Dislocation density < 1×10^{3} cm^{-2}
- **Very Active Research**: > 99 % of researchers

GaN on Sapphire Substrate

- **Poor Crystal Quality**: Dislocation density > 1×10^{9} cm^{-2}
- **Little Research**: < 1 % of researchers

Interest at 1992 JSAP Conference:

- **ZnSe** – Great Interest: *~ 500 Audience*
- **GaN** – Little Interest: *< 10 Audience*
- **GaN Actively Discouraged**:
  - "GaN has no future"
  - "GaN people have to move to ZnSe material"

First II-VI based laser diodes

Blue-green laser diodes

APL, Vol. 59, 1272, 1991

M. A. Haase, J. Qiu, J. M. DePuydt, and H. Cheng
3M Company, 201-1N-35 3M Center, St. Paul, Minnesota 55144

(Received 17 May 1991; accepted for publication 13 June 1991)

The first laser diodes fabricated from wide-band-gap II-VI semiconductors are demonstrated. These devices emit coherent light at a wavelength of 490 nm from a ZnSe-based single-quantum-well structure under pulsed current injection at 77 K. This is the shortest wavelength ever generated by a semiconductor laser diode.

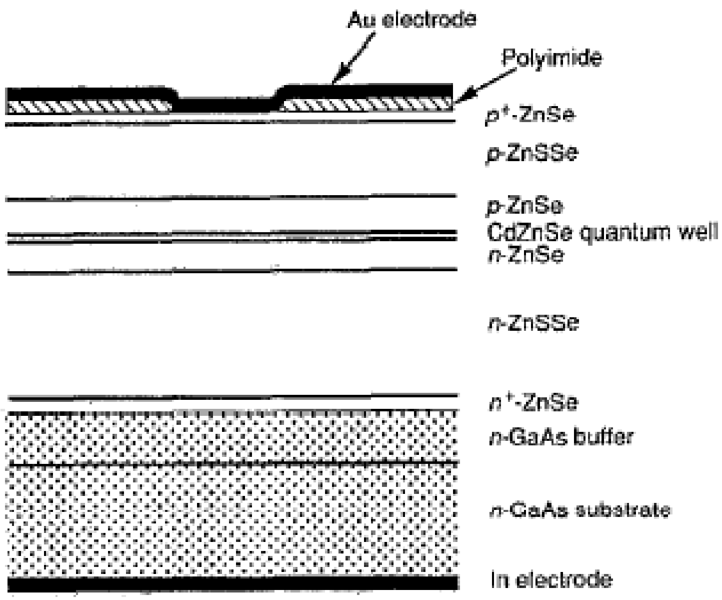


FIG. 1. A cross section of a blue-green laser diode.

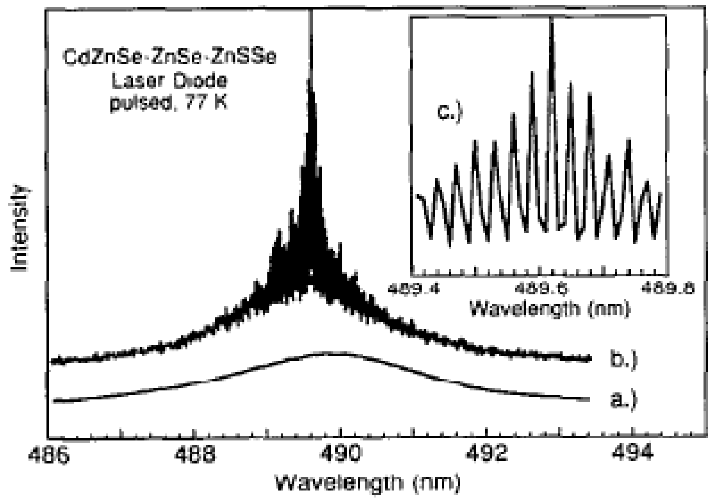
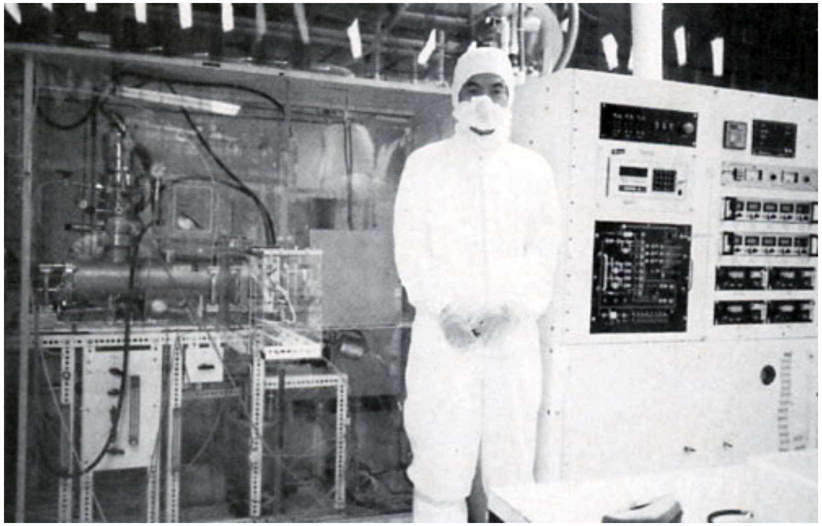


FIG. 3. The optical spectra for a blue-green laser diode: (a) below threshold; (b) above threshold; and (c) an expanded view of the lasing spectrum, taken with 0.01-nm steps. The device is 1020 μm long. Intensity scales for these three graphs are in arbitrary units, and are not the same.

1989: Starting Point of Research

Seeking to get Ph.D. by writing papers

- Very few papers written for GaN
- Great topic to publish lots of papers!



At University of Florida from 1988 to 1989 as a visiting researcher

Working at a small company:

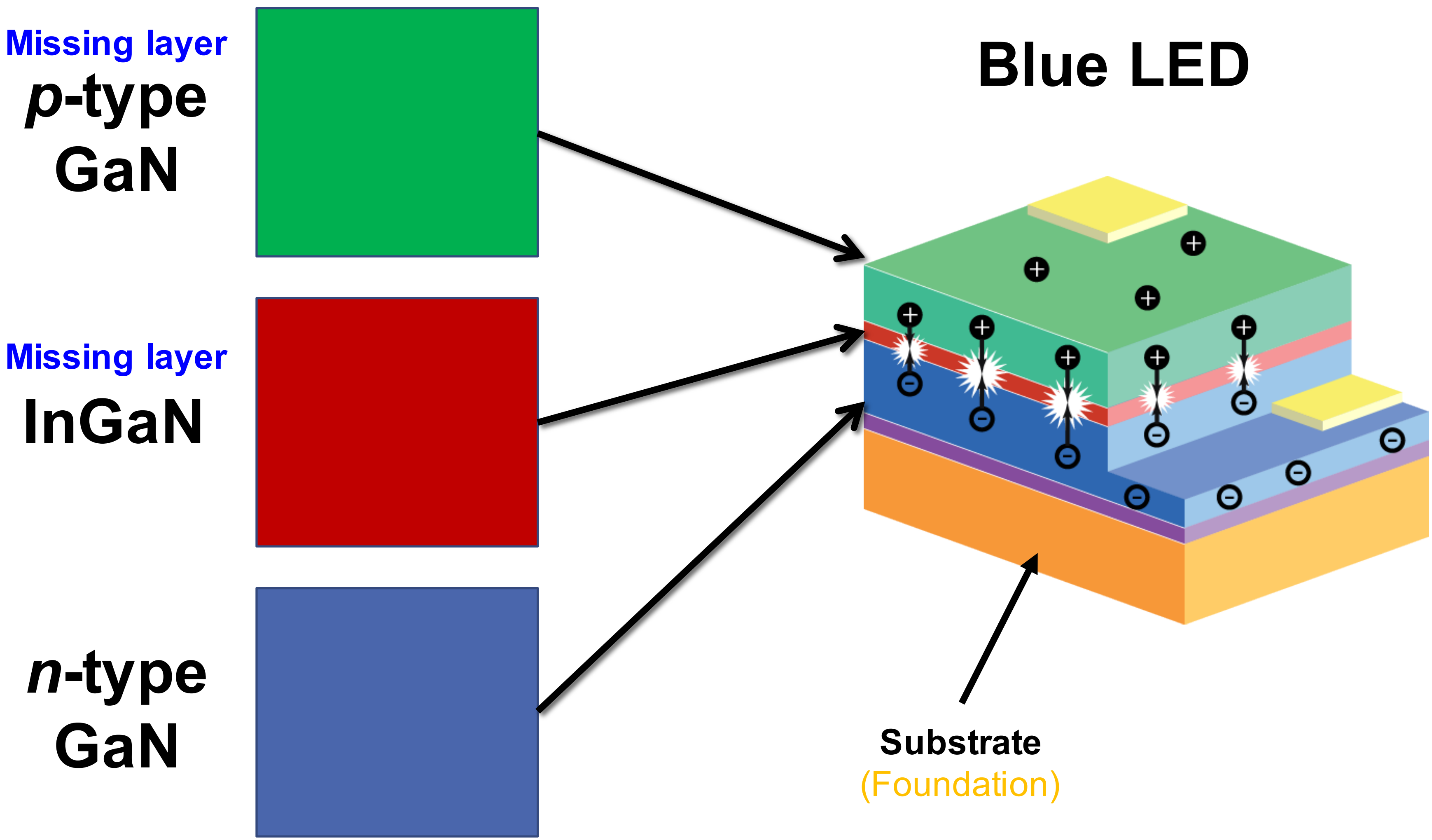
- Small Budget
- One Researcher

Commonly accepted in 1970s—1980s:

- LEDs need dislocation density < $1x10^3$ cm^{-2}

Never thought I could invent blue LED using GaN…

Blue LED is composed of three layers in 1989



Development of GaN and p-type GaN

GaN Matures

Invention: Two-Flow MOCVD

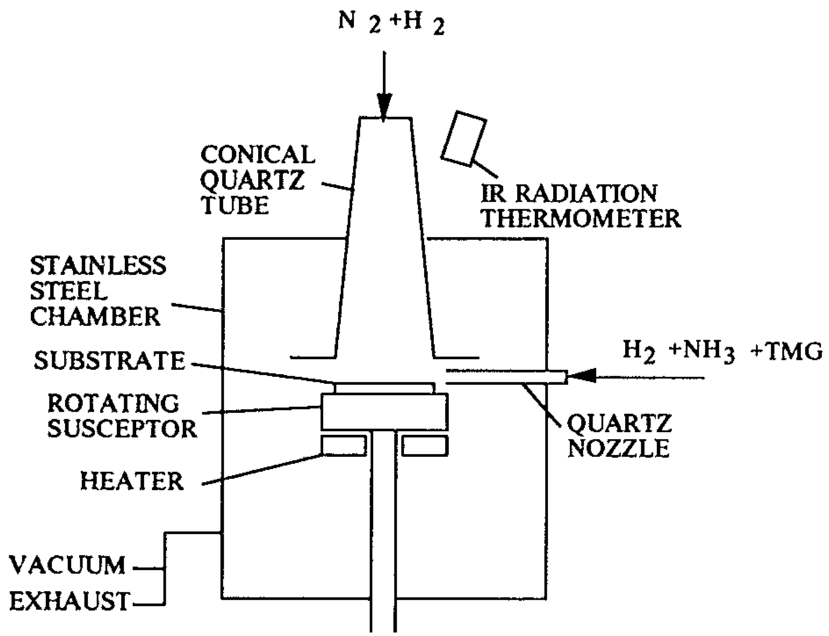
1991: S. Nakamura *et al.*, *Appl. Phys. Lett.*, **58** (1991) 2021—2023

Invention of **Two-Flow** MOCVD System
(MOCVD: Metal-Organic Chemical Vapor Deposition)

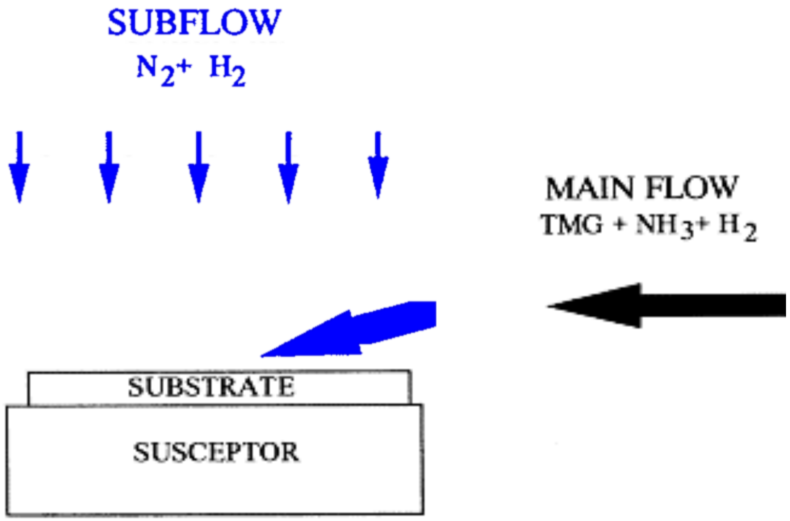
Reproducible, uniform**,** high quality GaN growth possible

Low carrier gas velocity: ~ 1 m/s

Schematic of Two-Flow MOCVD



Main Breakthrough:
Subflow to gently "push" gases down and improve thermal boundary layer



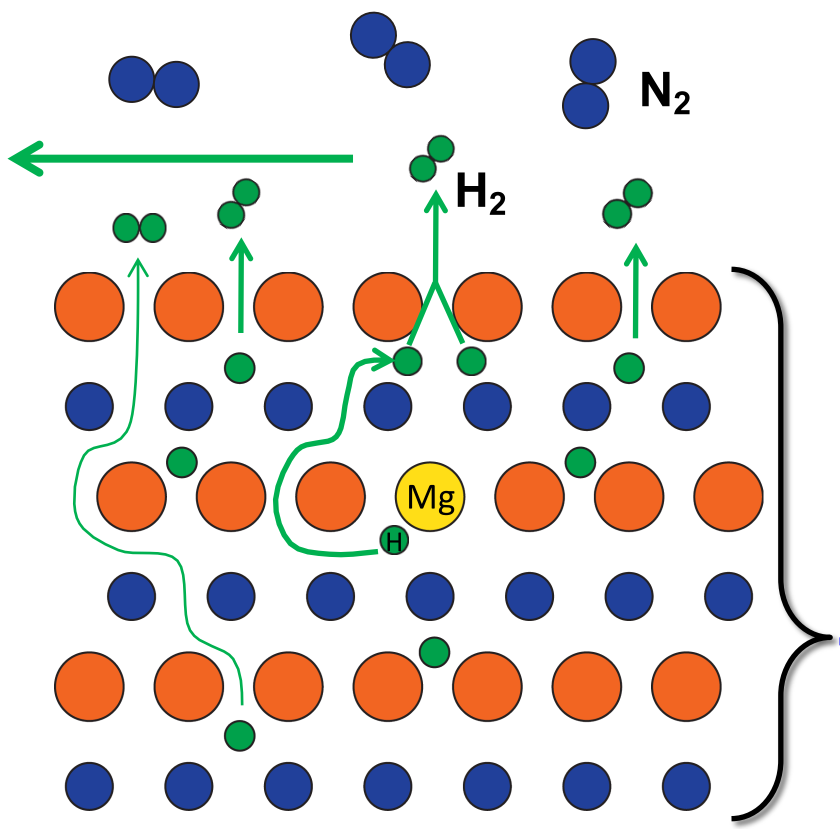
1992: Passivation and Activation of p-type GaN

1992: S. Nakamura *et al.*, *Jpn. J. Appl. Phys.*, **31** (1992) 1258—1266

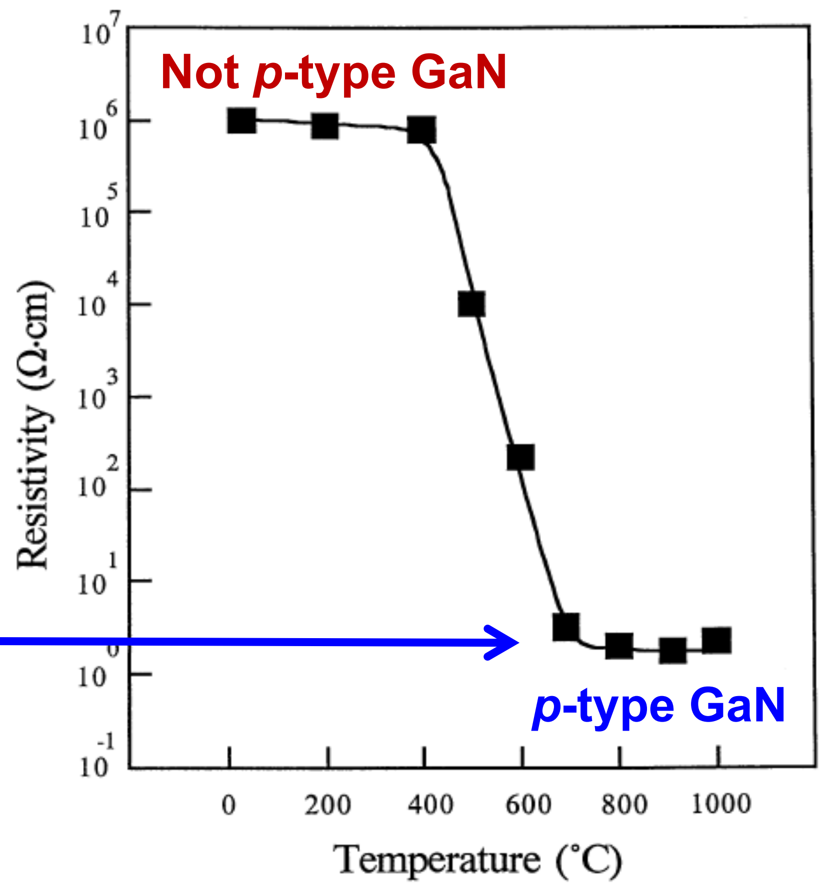
Prior: Everyone annealed in **H^+ containing** environment: **no *p*-type GaN**

Thermal Annealing in **H^+ free** environment: ***p*-type GaN, Industrial Process Compatible**

Thermal Annealing in hydrogen free



Resistivity of MOCVD GaN:Mg vs. T

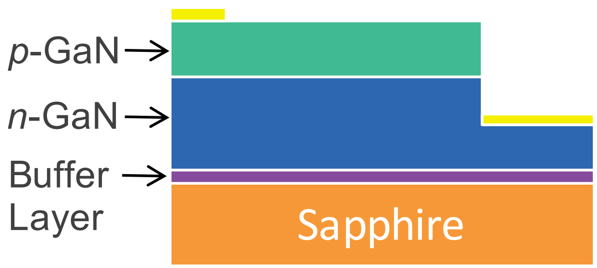


Development of InGaN (Emitting Layer)

ENABLING THE HIGH-EFFICIENCY LED

GaN Based Diodes

p-n GaN Homojunction



Needed

- **Tunable** Colors
- **Efficient** Device Structure
- Output Power **> mW**

Double Heterostructure

(Z.I. Alferov & **H. Kroemer**, 2000 Nobel Prize in Physics)

Confines carriers, yielding higher Quantum Efficiencies

_p-n_ GaN Homojunction (as developed by Akasaki & Amano in 1989)

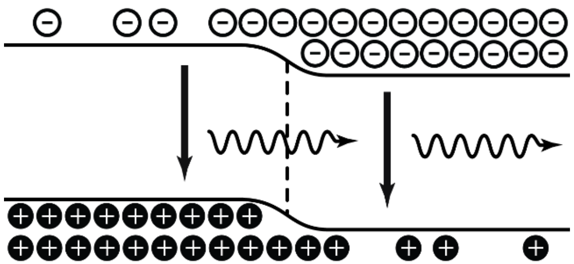
- **Good Crystal Quality**
- **Very Dim** Light Production
- Very **Inefficient**
- Output power **<< mW**
- **360nm UV (Eg-3.4eV) emission, not blue emission**

Not Suitable for LEDs

Homojunction vs. Double Heterostructure

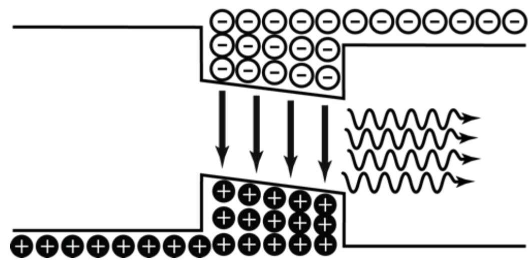
Energy Band Diagrams

Homojunction LED



p-type *n*-type

Double **Hetero**structure LED



p-type **InGaN Active Layer** *n*-type

Internal Quantum Efficiency

$$\eta_{IQE} = \frac{\text{Light generated}}{\text{Electrons injected}} = \frac{R_{radiative}}{R_{radiative} + R_{non-radiative}} = \frac{Bn^2}{An + Bn^2 + Cn^3}$$

Shockley-Read-Hall (SRH) (An) ***Spontaneous Emission*** (Bn^2) ***Auger*** (Cn^3)

Double heterostructures **increase carrier concentrations (*n*)** in the active layer and **enhance radiative recombination** rates (more light generated).

High Quality InGaN Layers

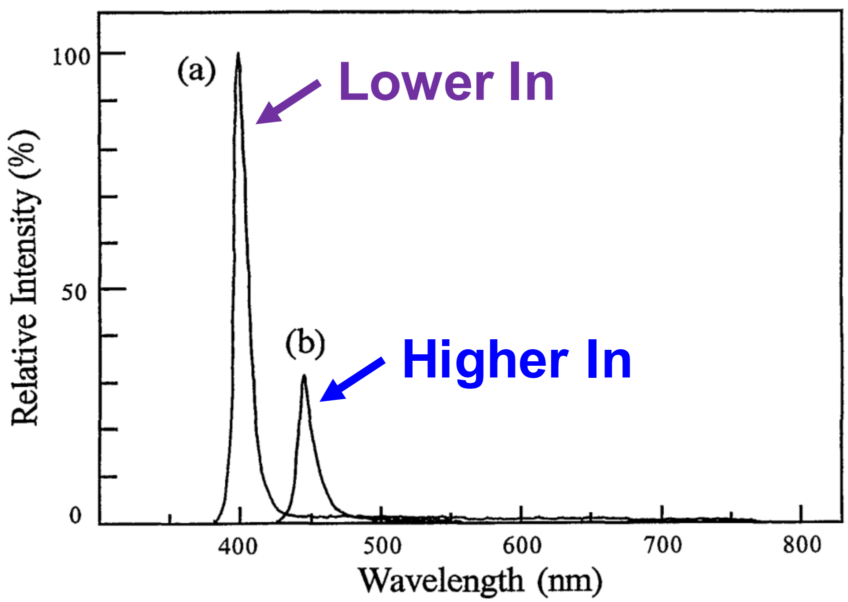
1992: S. Nakamura *and Mukai*, *Jpn. J. Appl. Phys.*, **31** (1992) L1457—L1459

Enabling Technology: **Two-Flow MOCVD**

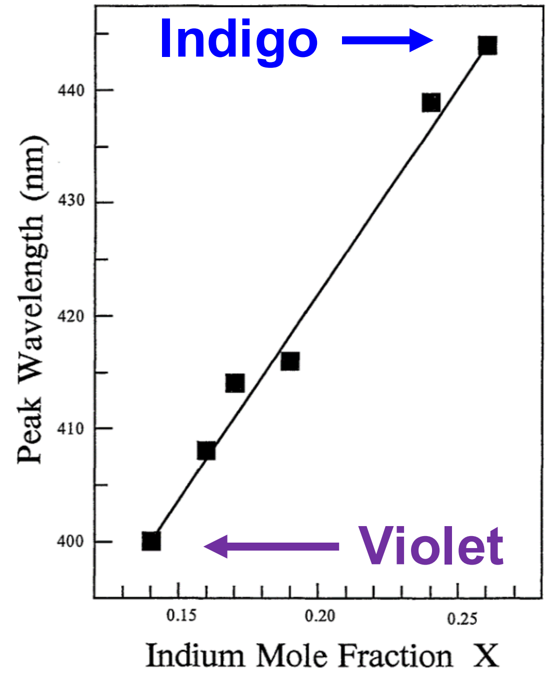
High Quality InGaN Growth with **Band-to-Band Emission**

Controllably vary Indium Concentration and hence color

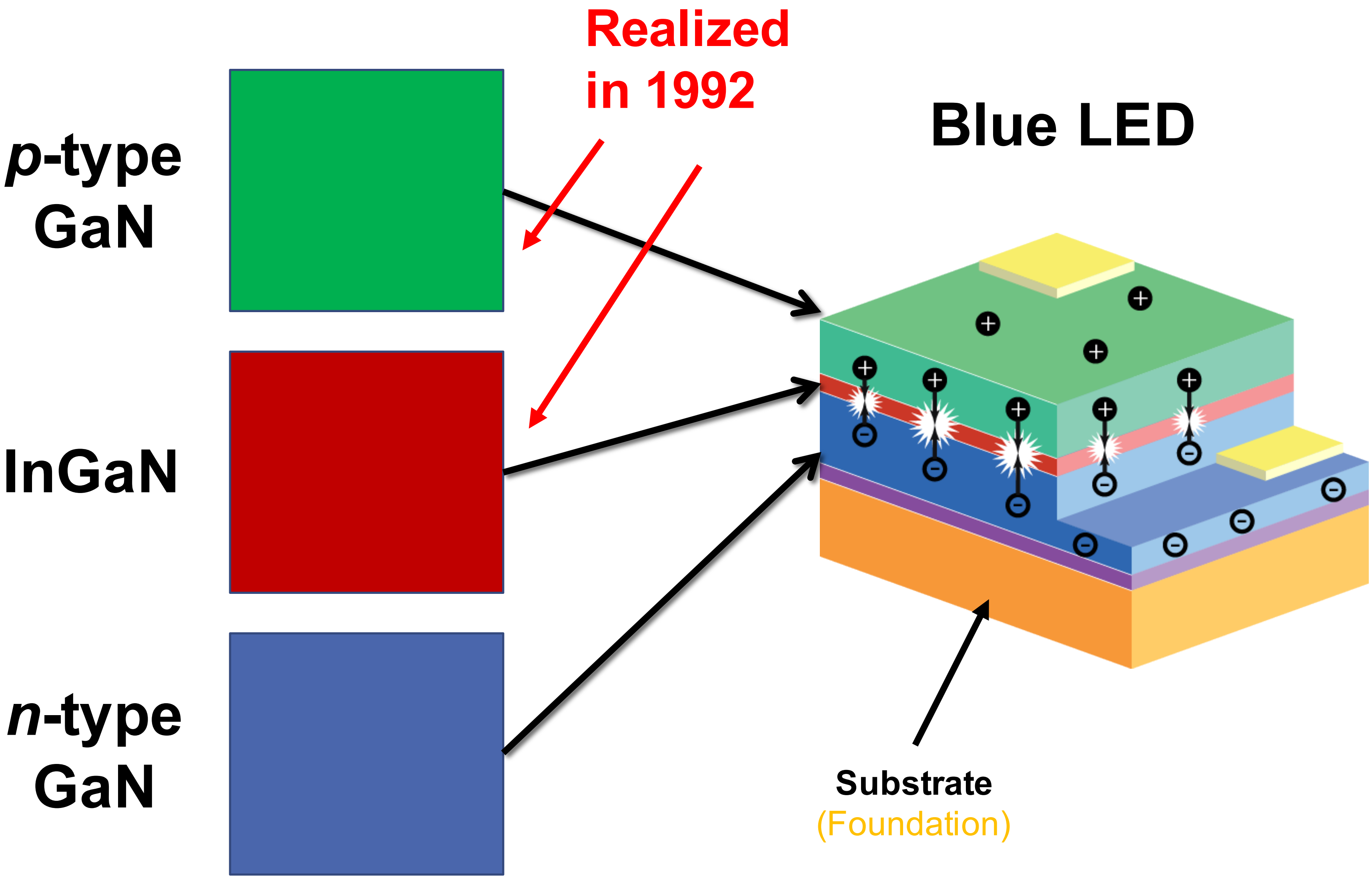
Photoluminescence Spectra of InGaN



Wavelength vs. Indium Fraction



And Assemble



First High Brightness InGaN LED

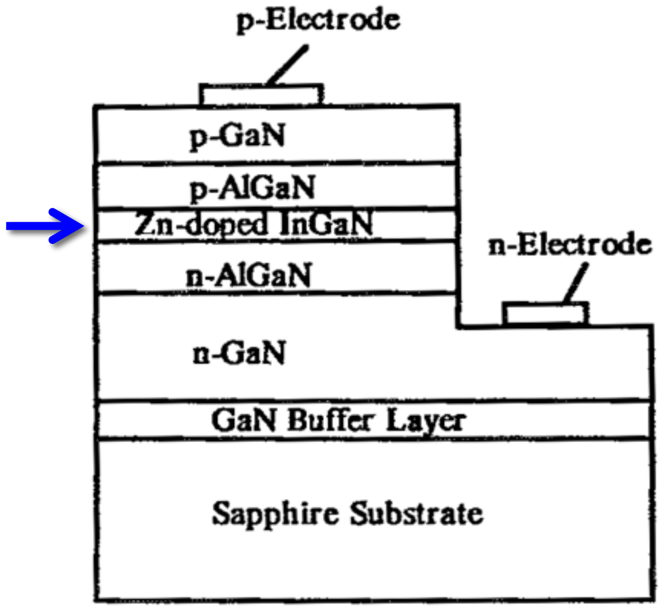
1994: S. Nakamura *et al.*, *Appl. Phys. Lett.*, **64** (1994) 1687—1689

Breakthrough Device with Exceptional Brightness

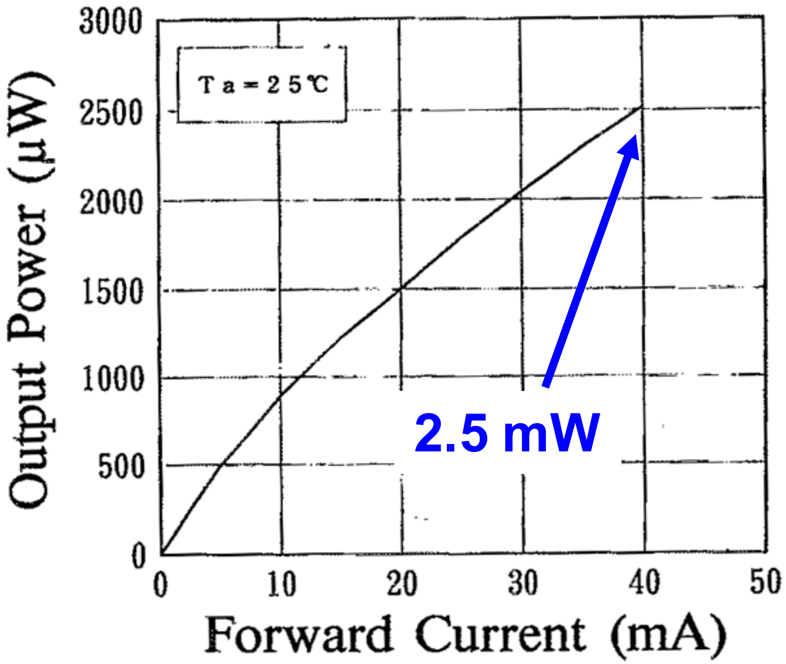
(2.5 mW Output Power @ 450 nm (Blue))

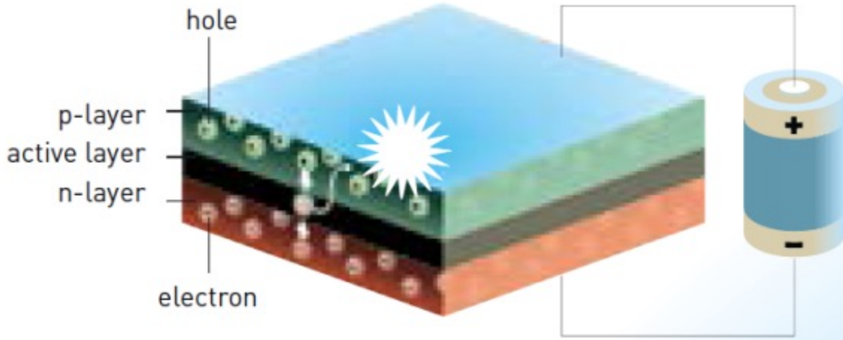
Optimization of **thin InGaN Active Layer**

Blue InGaN **Double Heterostructure (DH)** LED



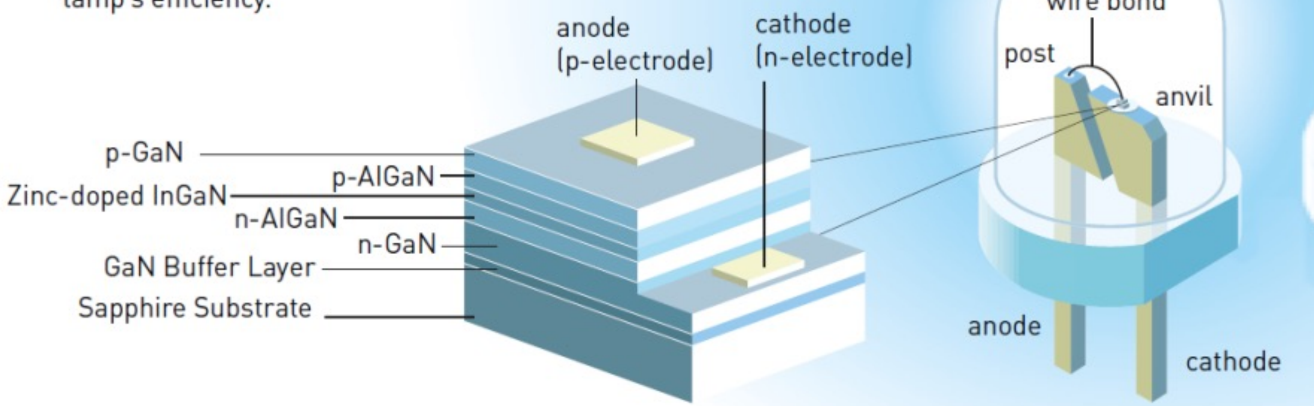
Output Power vs. Current





The heart of the LED. A light-emitting diode consists of several layers of semiconducting materials. Electrical voltage drives electrons from the n-layer and holes from the p-layer to the active layer, where they recombine and light is emitted. The light's wavelength depends entirely on the semiconducting material used. The LED is no larger than a grain of sand.

Blue LED lamp. The light-emitting diode in this lamp consists of several different layers of gallium nitride (GaN). By mixing in indium (In) and aluminium (Al), the Laureates succeeded in increasing the lamp's efficiency.



The principle for a light-emitting diode – LED (upper left) and an example of a blue LED lamp.

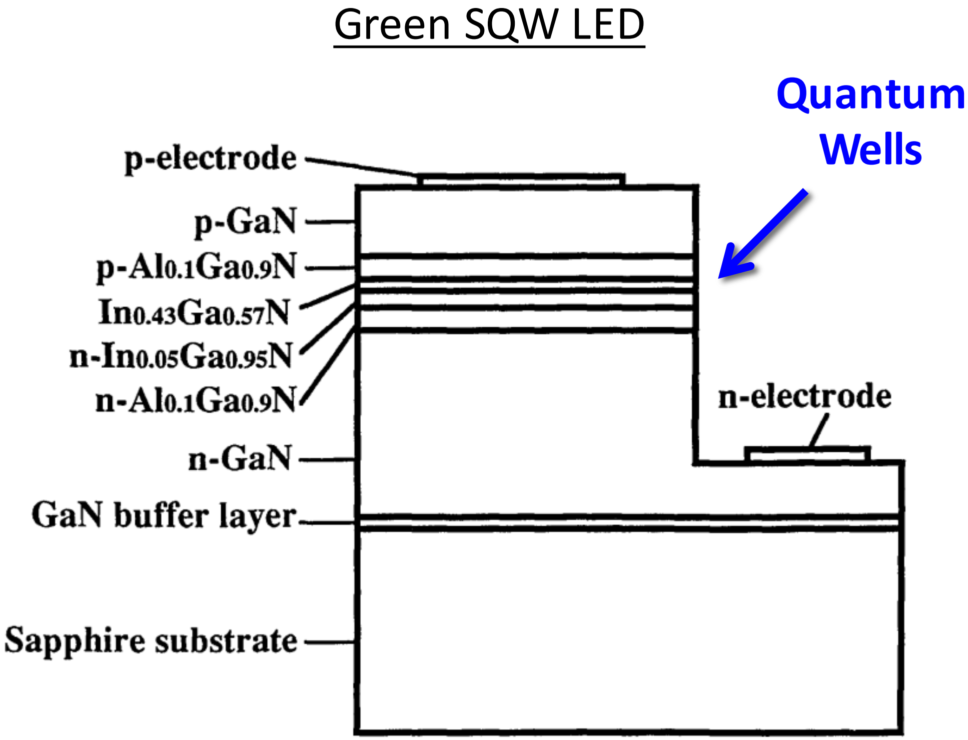
Source: www.nobelprize.org

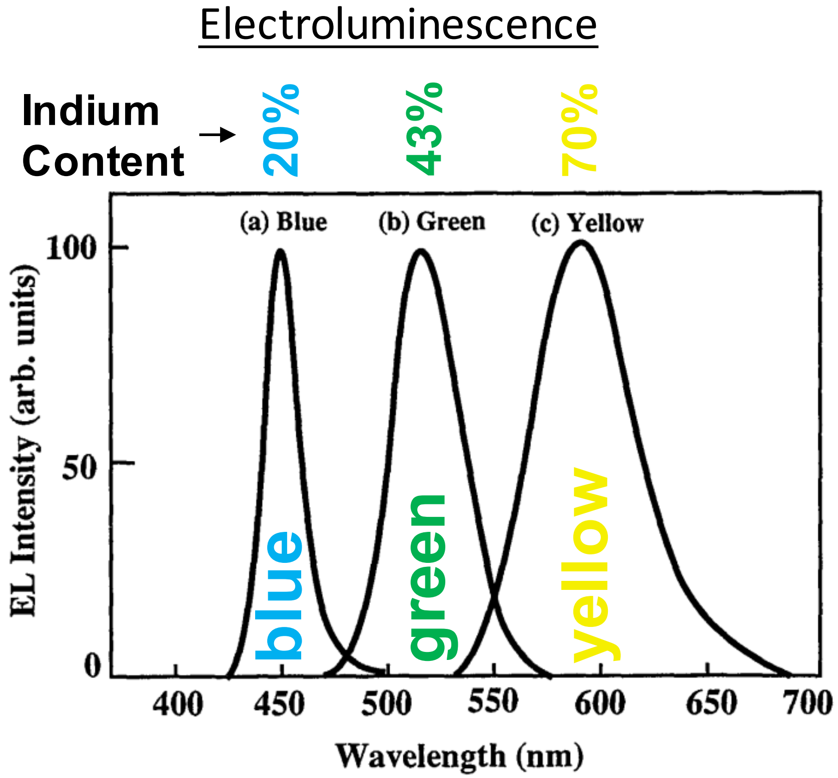
1st InGaN QW Blue/Green/Yellow LEDs

1995: S. Nakamura *et al.*, *Jpn. J. Appl. Phys.*, **34** (1995) L797—L799

High Brightness LEDs of **varying colors** by increasing Indium content.

Demonstration of **Quantum Wells** (QWs).



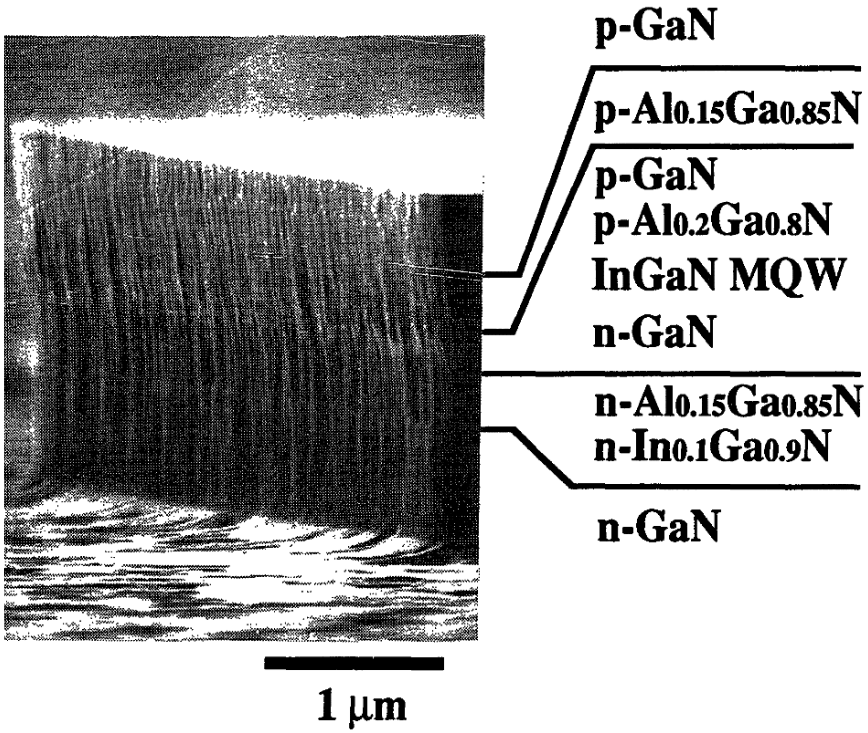


1st Violet InGaN MQW Laser Diode

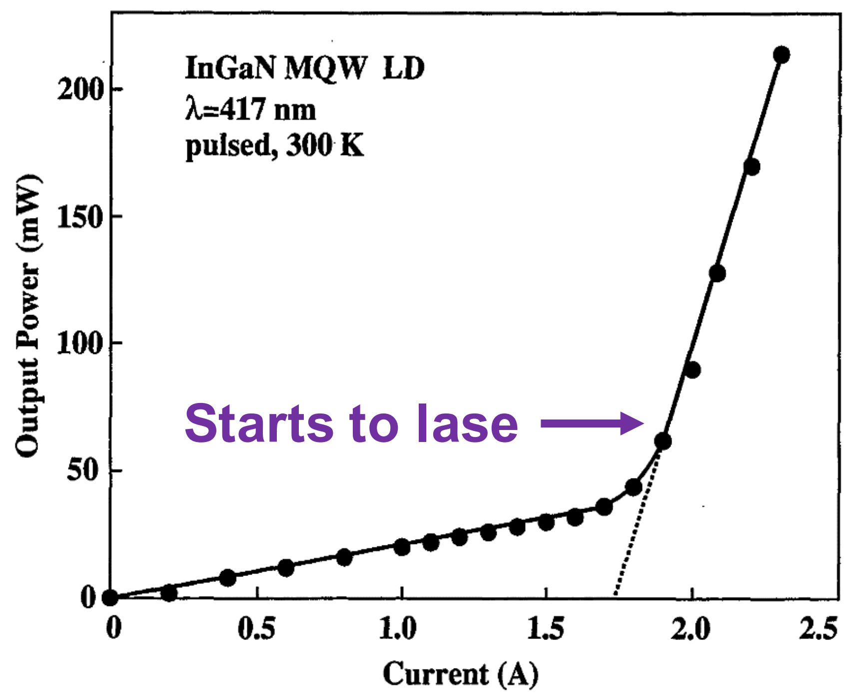
1996: S. Nakamura *et al.*, *Jpn. J. Appl. Phys.*, **35** (1996) L74—L76

First Demonstration of a **Violet Laser** using multiple QWs.

Laser Structure using InGaN



Light Output vs. Current



Contributions towards efficient blue LED

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

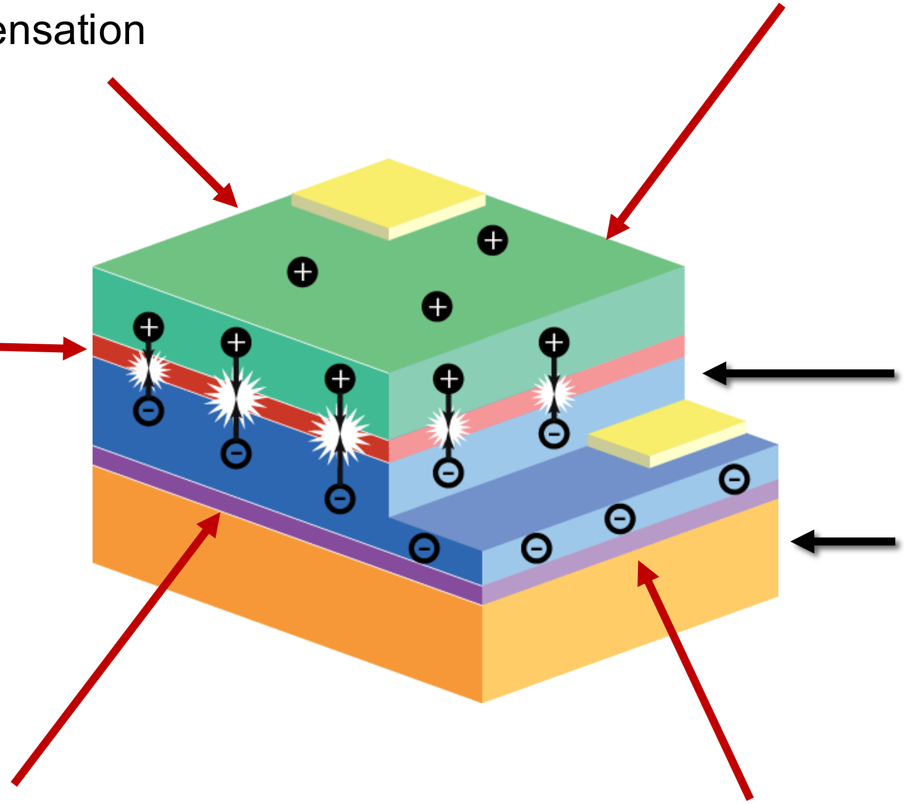
Hydrogen passivation was clarified as an origin of hole compensation

***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**

2nd Generation LED:
GaN on GaN LEDs by Soraa Inc.

Comparison of LED 1.0 vs 2.0

1st generation LEDs are grown on sapphire, SiC and Si substrates
---Hetero-epitaxial growth---

2nd generation LEDs are grown on GaN substrates
---Homo-epitaxial growth---

Shuji and LED History

First Blue LEDs

Soraa Founded

GaN-on-GaN™ Full Spectrum
Lamp Portfolio

1962

1993

2006

2008

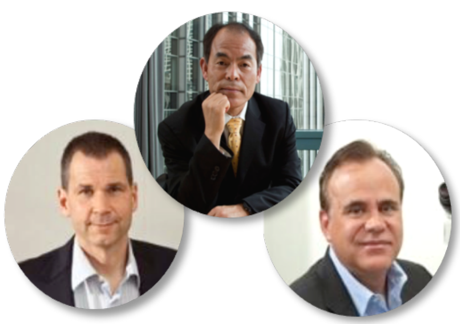
2012

2014

NOW:

Laser Research for the future

First LED (red)



GaN on GaN
LEDs invented

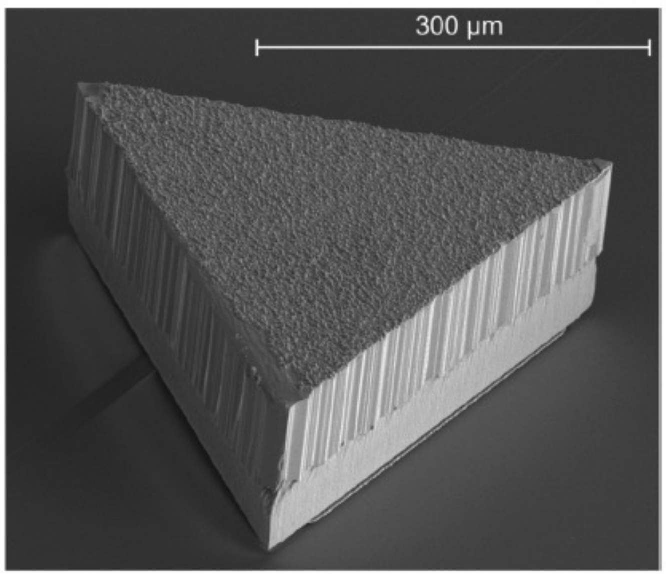
First GaN on GaN™ Full
Spectrum Lighting
Product

GaN on GaN LED

APPLIED PHYSICS LETTERS **106**, 031101 (2015)

Bulk GaN flip-chip violet light-emitting diodes with optimized efficiency for high-power operation

Christophe A. Hurni,[a)] Aurelien David, Michael J. Cich, Rafael I. Aldaz, Bryan Ellis, Kevin Huang, Anurag Tyagi, Remi A. DeLille, Michael D. Craven, Frank M. Steranka, and Michael R. Krames
Soraa, Inc., 6500 Kaiser Dr., Fremont, California 94555, USA



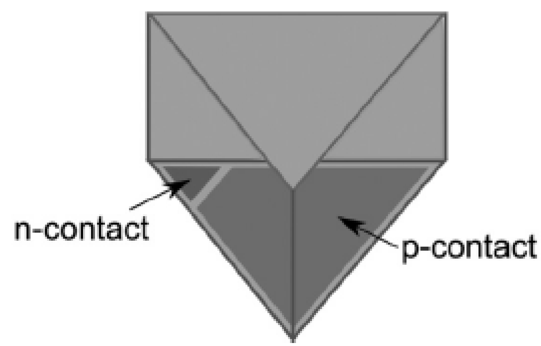
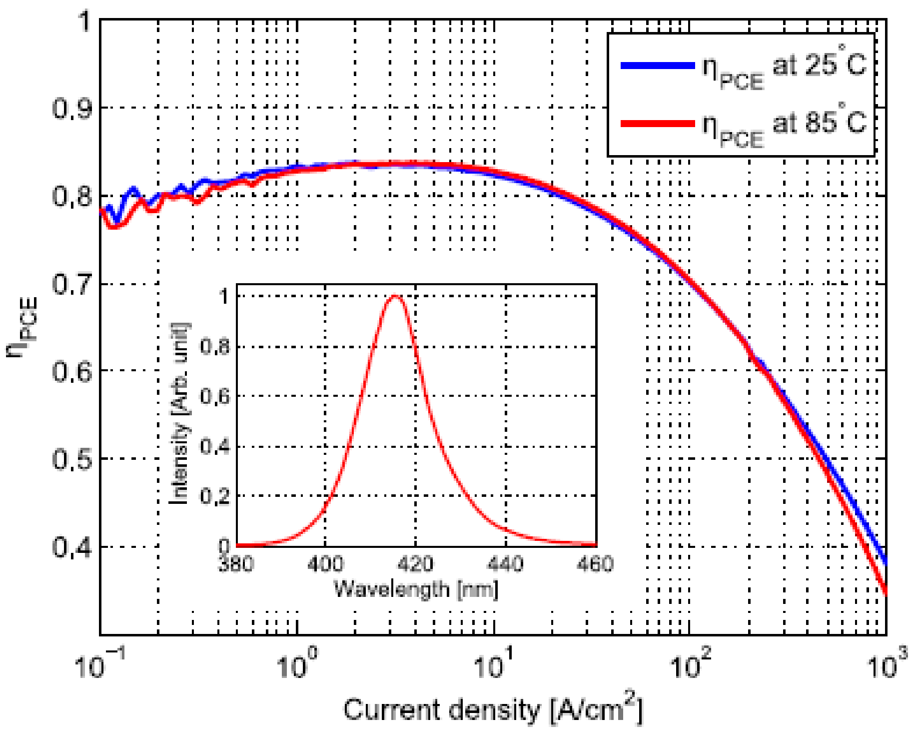


FIG. 1. Scanning electron microscope image of the triangular volumetric flip-chip device (top) and corresponding schematic (bottom).

Wall Plug Efficiency of GaN on GaN LED

Power Conversion Efficiency= Wall Plug Efficiency

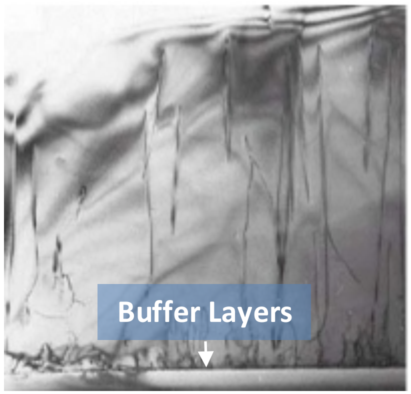


Wall Plug Efficiency of GaN on GaN violet LED is 75% at a current density of 35A/cm^2

Wall Plug Efficiency of commercially available blue LED is 40% at a current density of 35A/cm^2

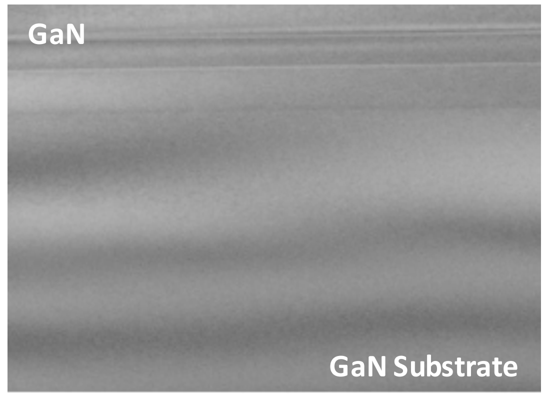
SORAA™

Standard (Sapphire, SiC, Si)



Foreign substrate

SORAA GaN on GaN™



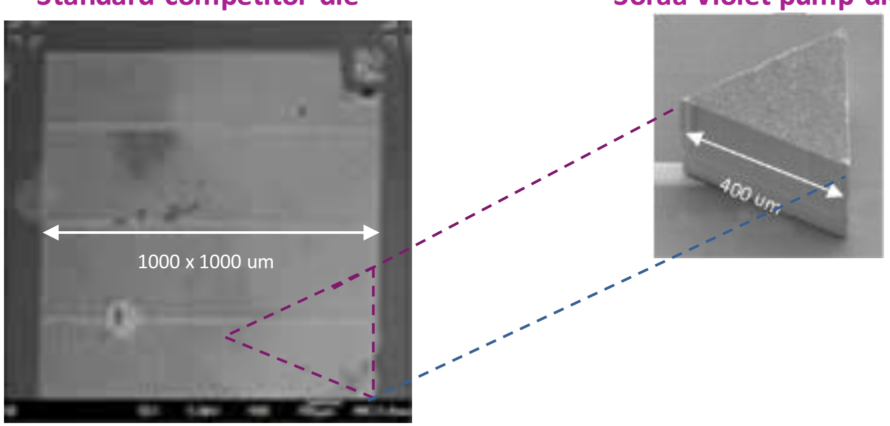
Up to 1000x lower dislocation density

1000x less defects:

- Greater lumens per mm^2

Standard competitor die

Soraa violet pump die



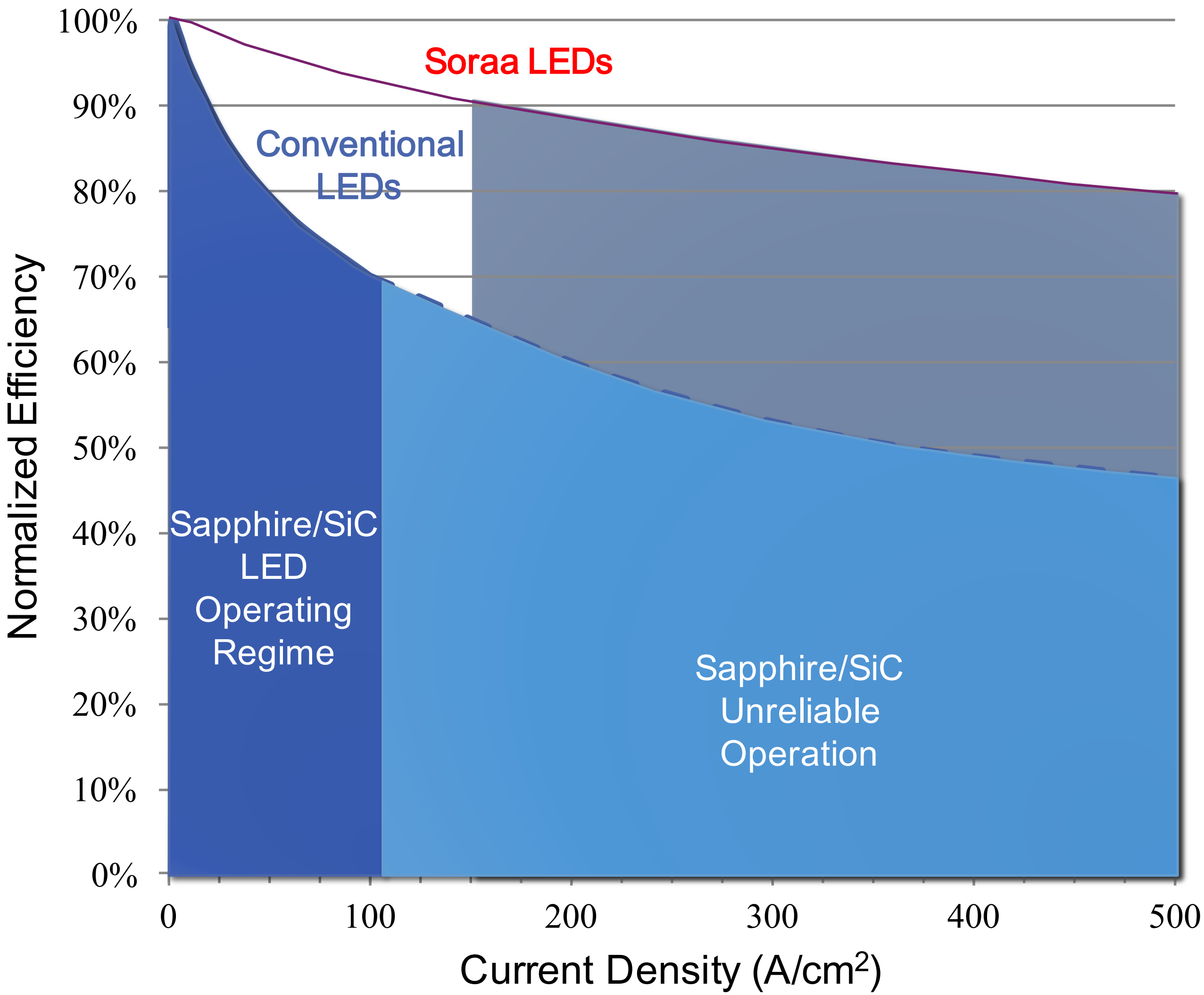
Smaller die size enables:

- Less die area = Lower Costs

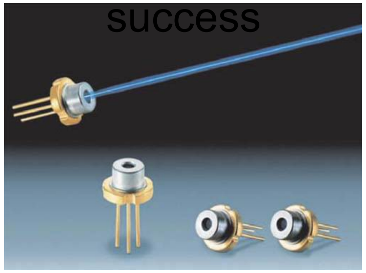
POINTSOURCEOPTICS™

- Optimized lighting
- Perfect beams

SORAA GAN ON GAN™ = FUNDAMENTAL ADVANTAGE



Blue Lasers: $1kA/cm^2$+
10+ Years commercial success



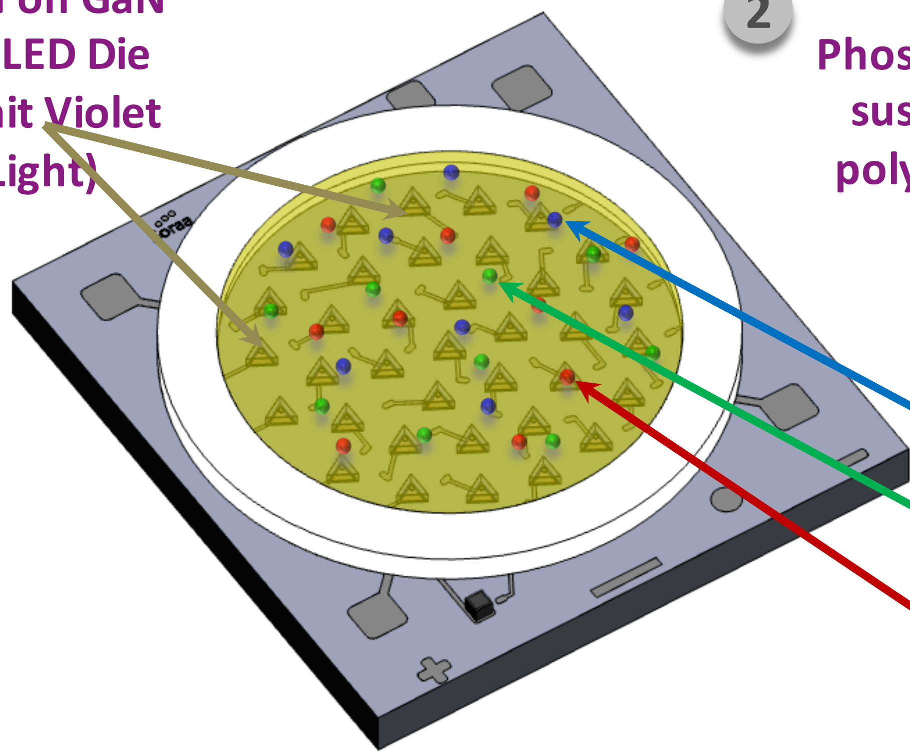
What's VP_3?

SORAA

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

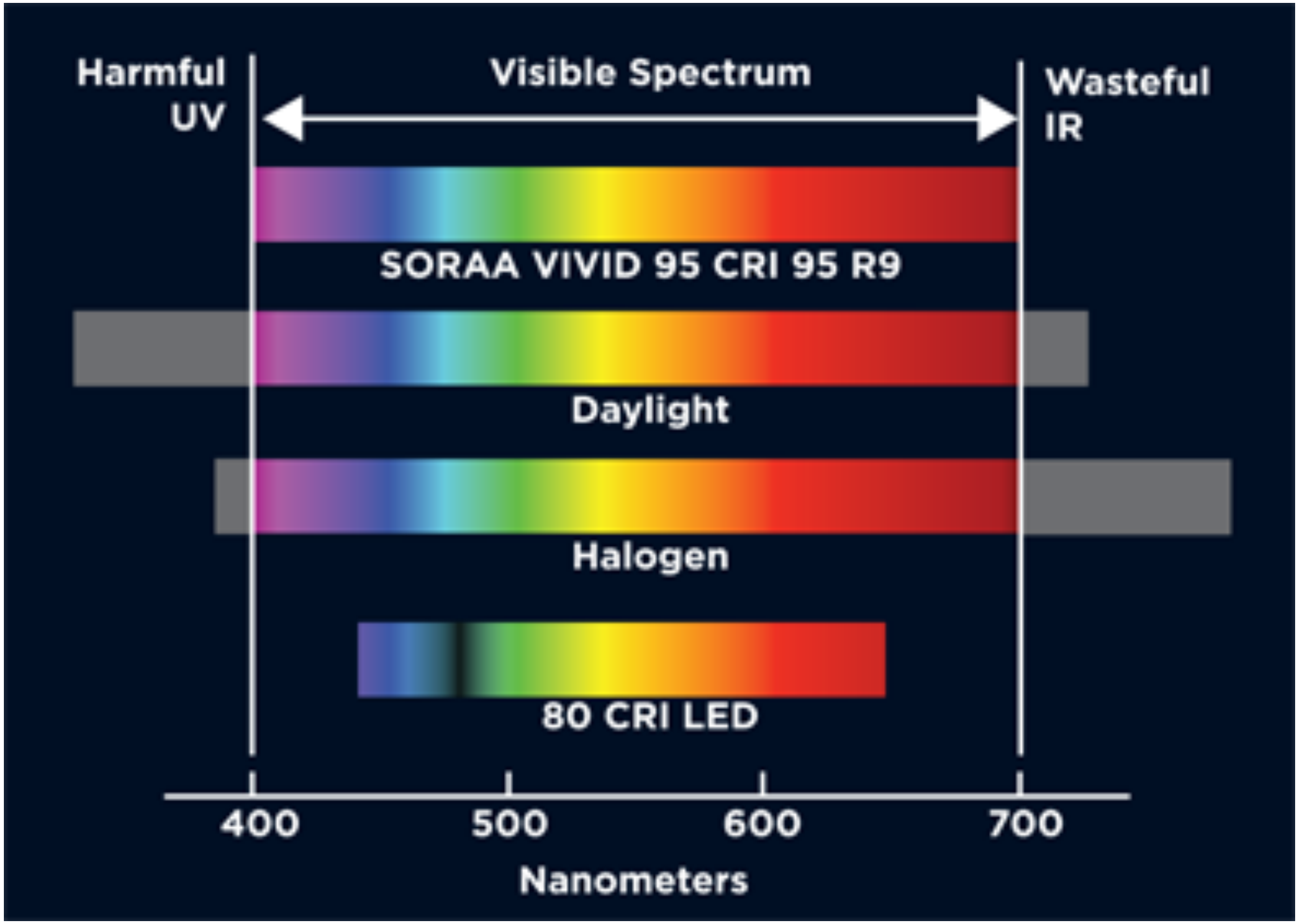
Green

Red

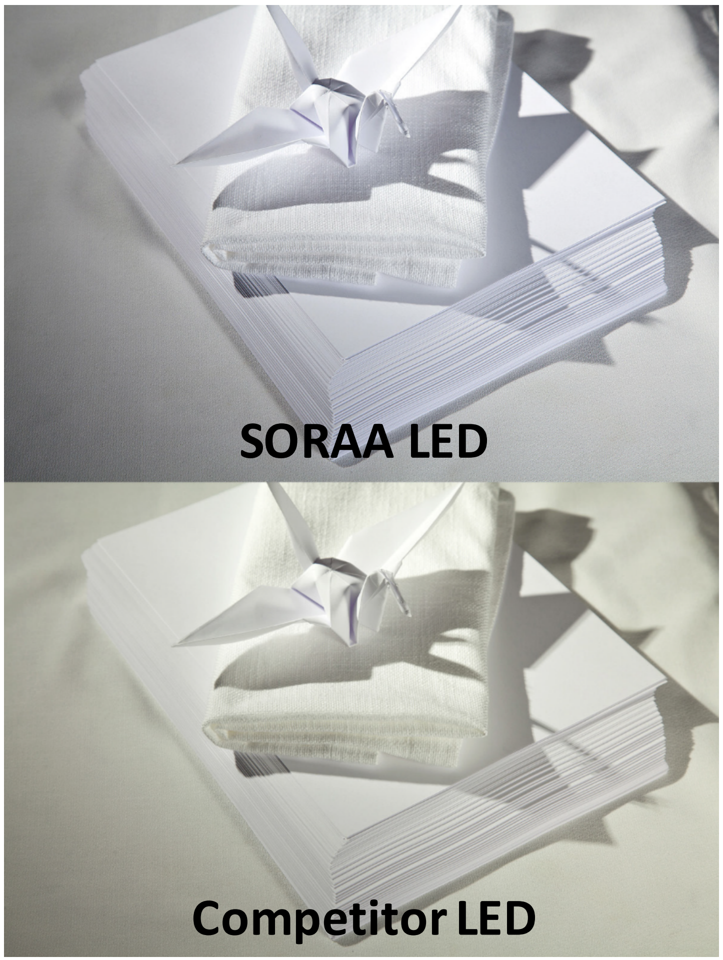
3 Resulting in Full-visible-spectrum light

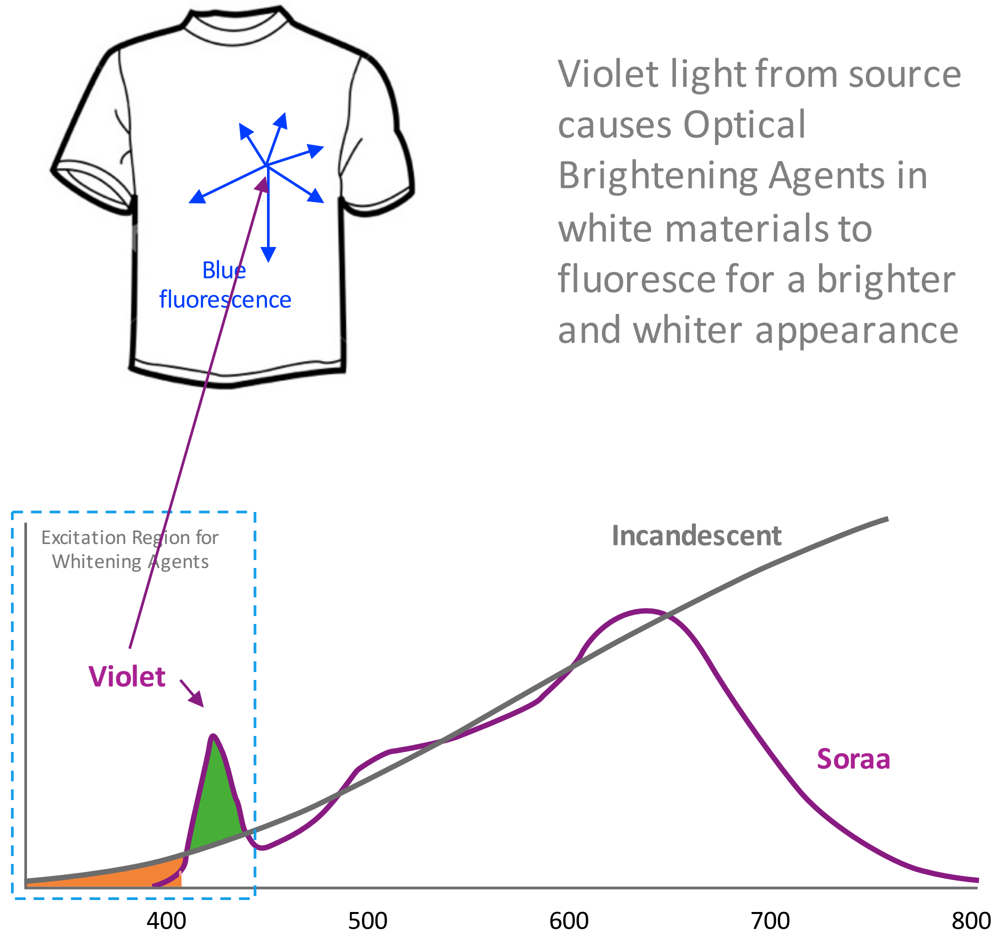
What's VP_3?

VP_3 = Violet and 3 Phosphor



VP$_3$ NATURAL WHITE

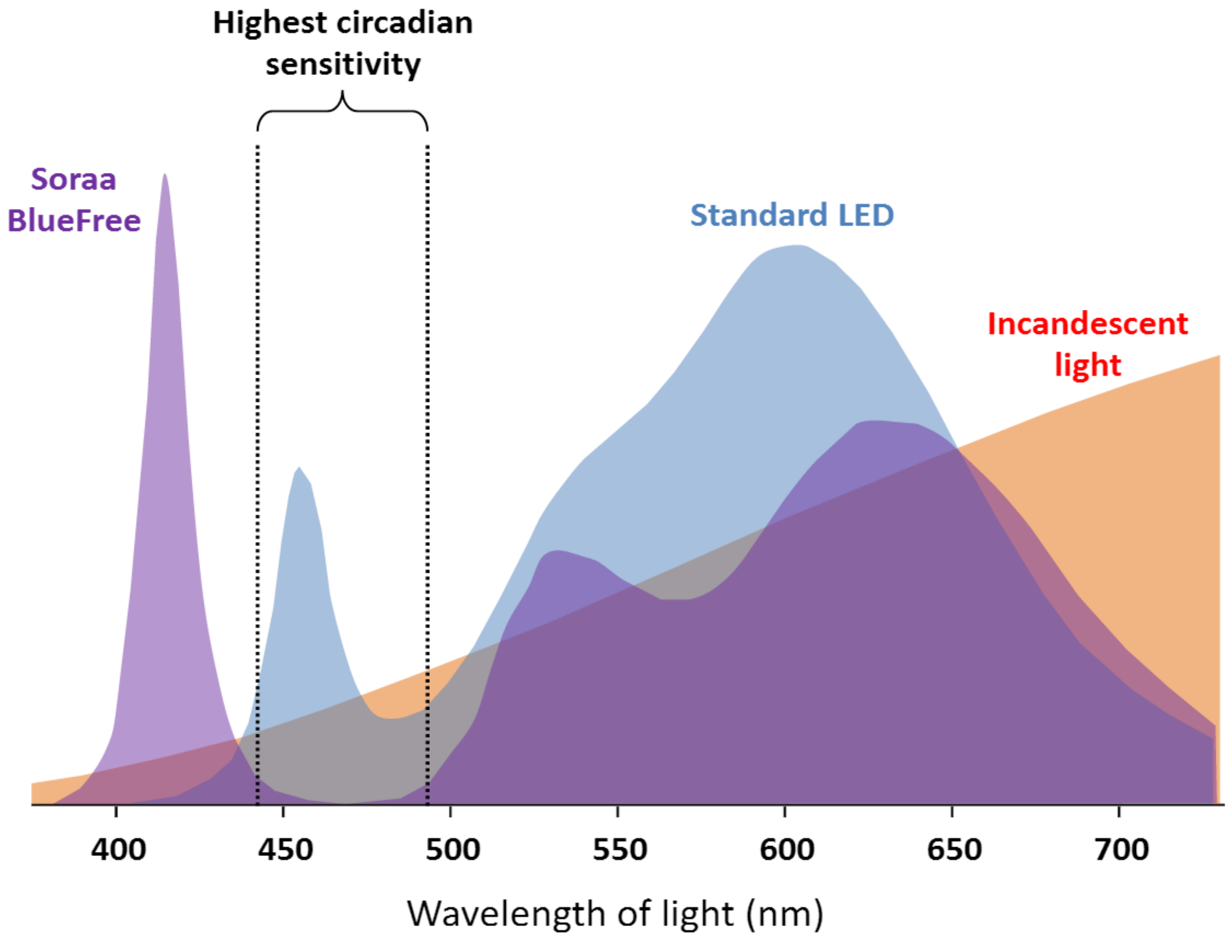




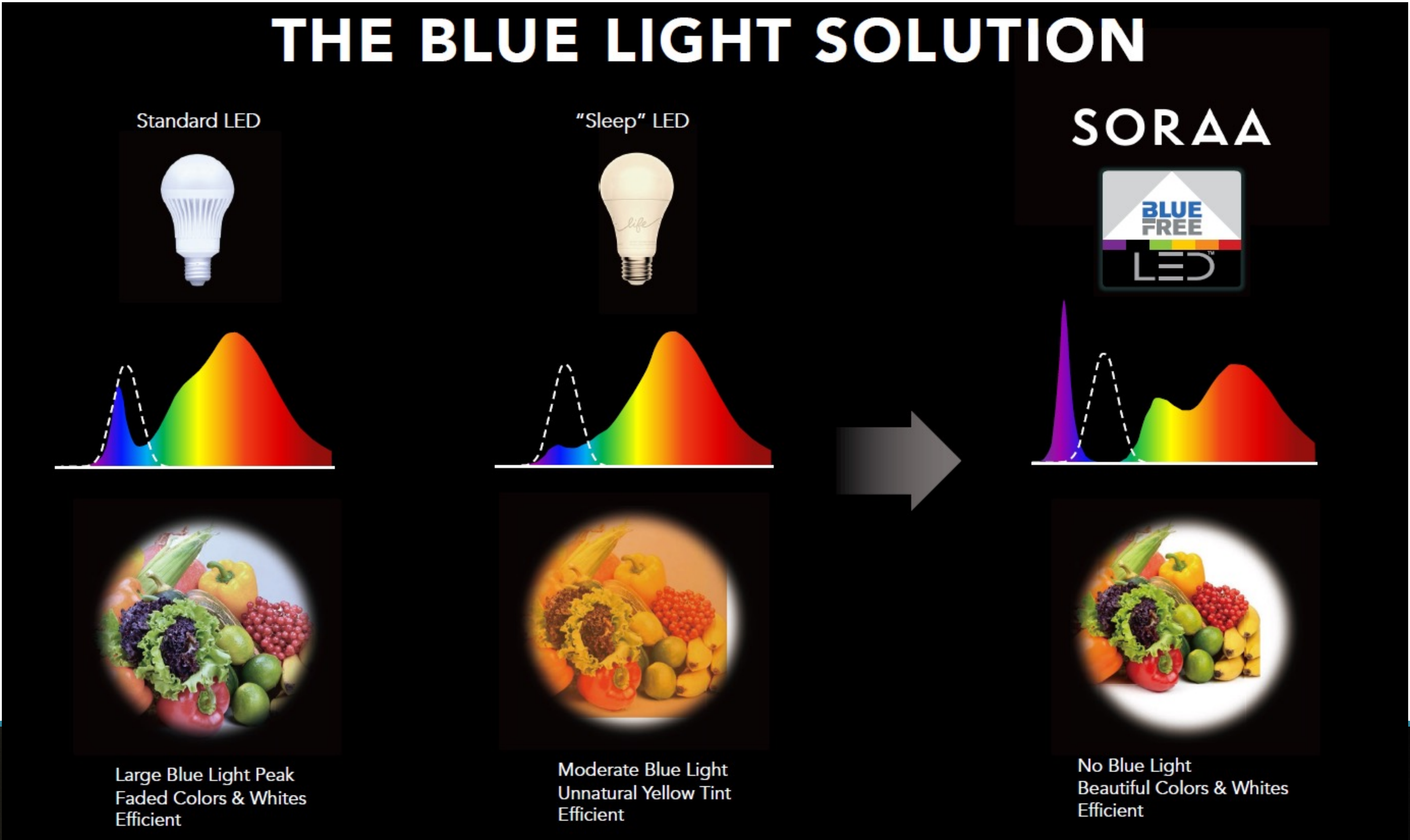
Violet light from source causes Optical Brightening Agents in white materials to fluoresce for a brighter and whiter appearance

New Soraa's Helia Bulb Lamp

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



SORAA


THE BLUE LIGHT SOLUTION
Standard LED
"Sleep" LED
SORAA
BLUE FREE LED
Large Blue Light Peak
Faded Colors & Whites
Efficient
Moderate Blue Light
Unnatural Yellow Tint
Efficient
No Blue Light
Beautiful Colors & Whites
Efficient

New Soraa's Helia Bulb Lamp

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

CES 2017 Innovation award

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
Follow us: @digitaltrends on Twitter | DigitalTrends on Facebook

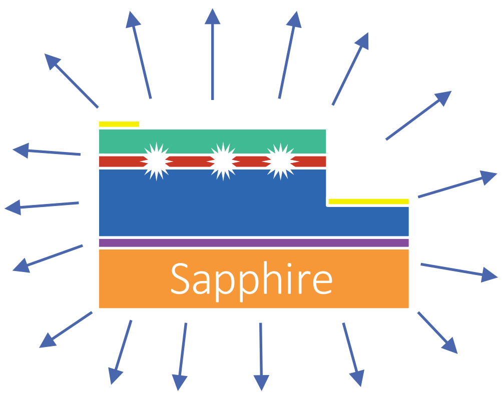
3^{nd} Generation SSL: Laser Lighting

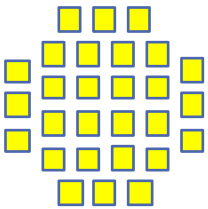
UCSB's Vision

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

	Device	60 W Incandescent Equivalent	External Quantum Efficiency LED/Laser vs. Current Density

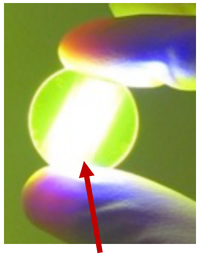
LED





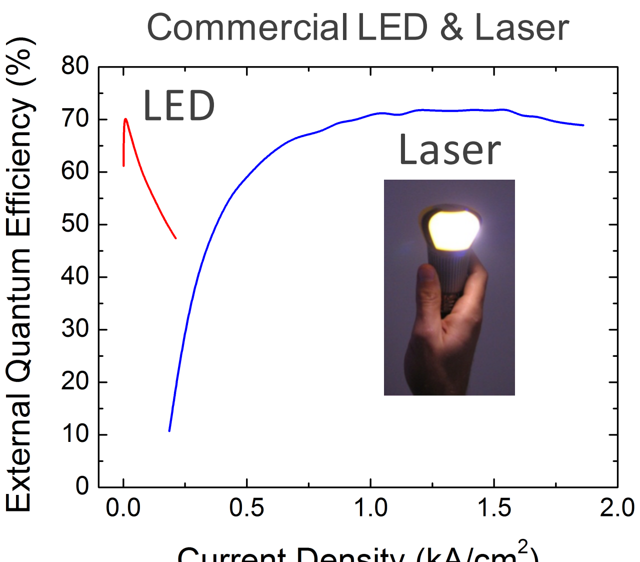
28 mm^2

Laser



Phosphor Strip

0.3 mm^2



M. Cantore *et al.*, UCSB

100’ Laser TV at 2014 Las Vegas CES

The cost of laser TVs should eventually be less than other TV technologies

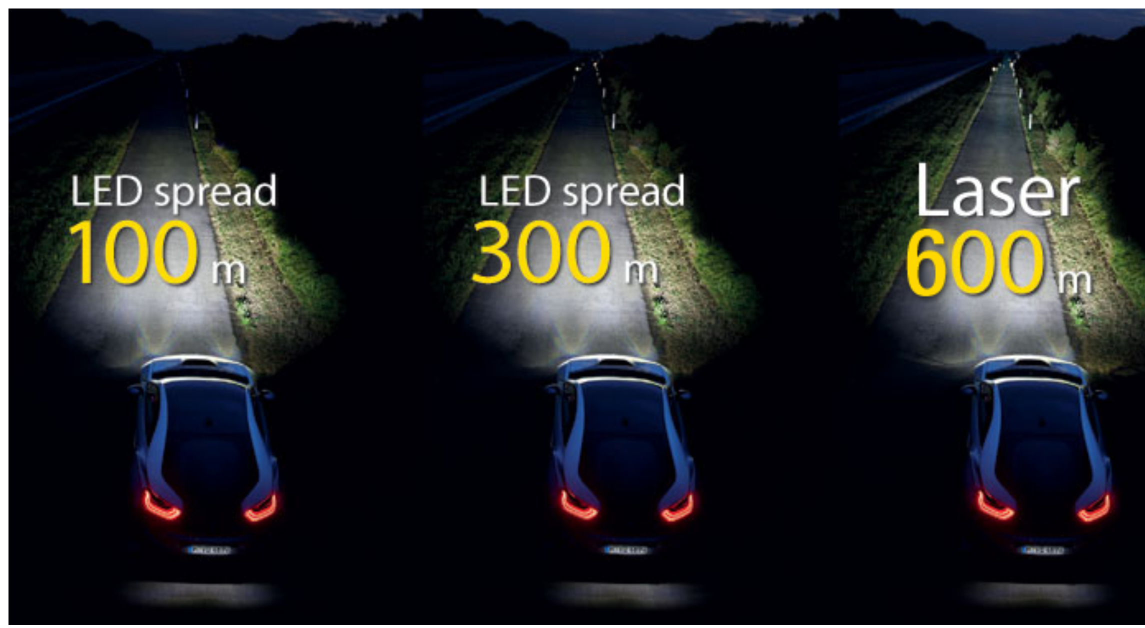
Pico projector with Laser Lighting

Laser Diodes – Light of the Future

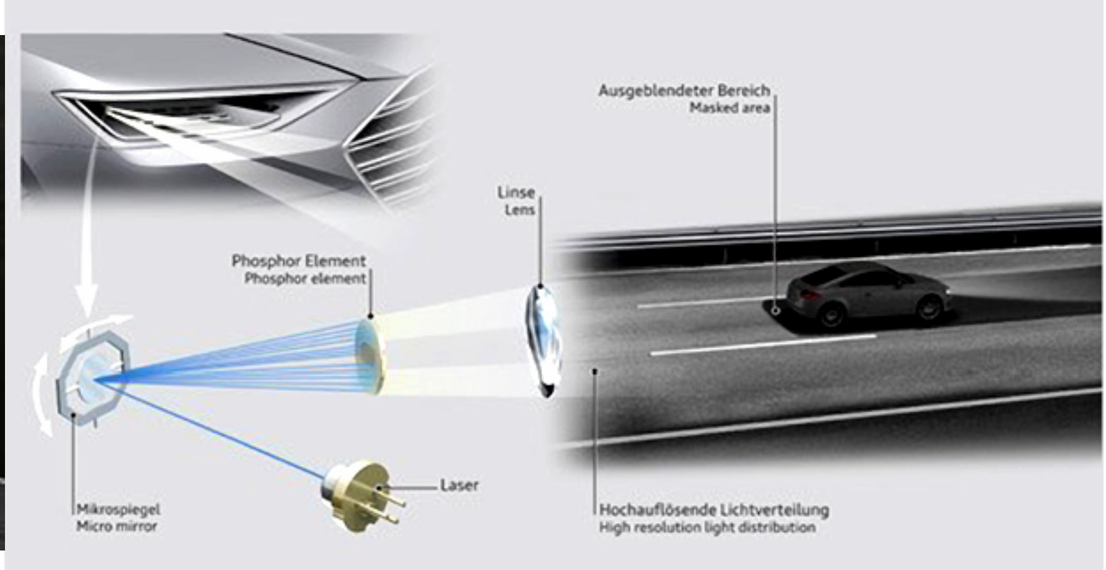
Laser Headlights

Laser Projectors

100 inch TV



Audi Pixelated Laser Headlights Light the Road



Each mirror can be tilted up to 5,000 times per second, breaking the beam into pixels that can hit the roadway and also highlight traffic signs. By analyzing the feed from onboard cameras the system can steer the light away from the oncoming traffic. That way, this highest of all high beams can't blind other drivers.

BMW with Laser Lighting Headlights

BMW with laser headlights
(available in US!)

Researchers at UCSB: SSLEEC in 2016

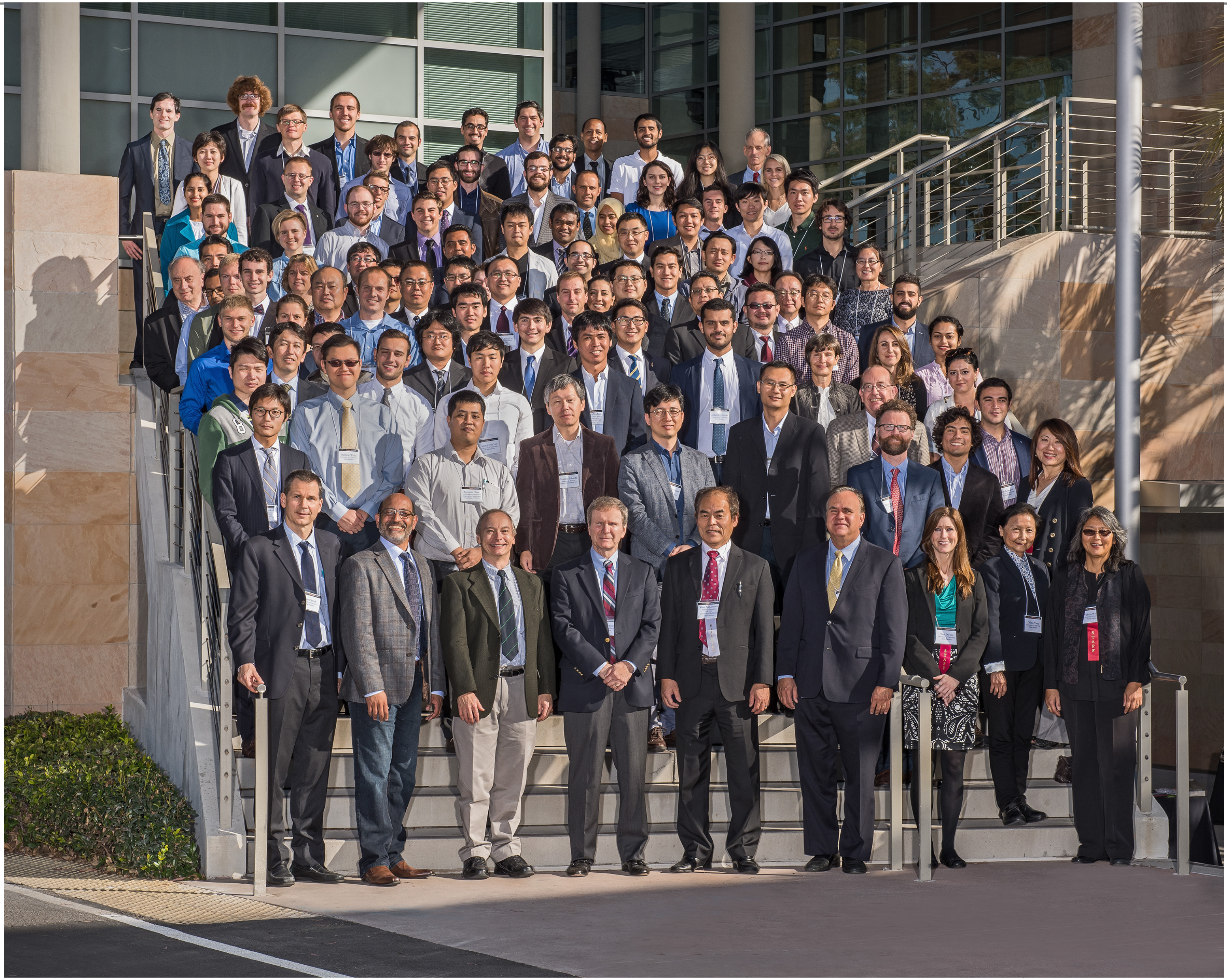


Photo by Tony Mastres