History and Recent Progress of LED

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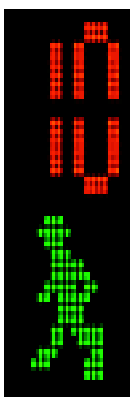
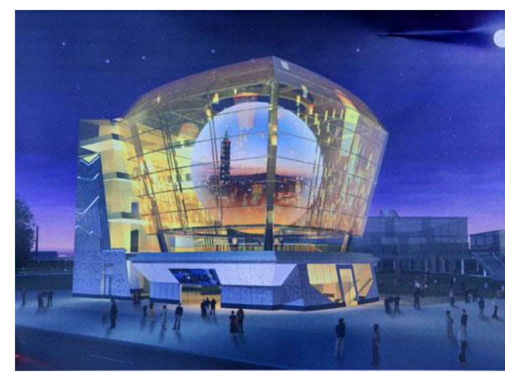
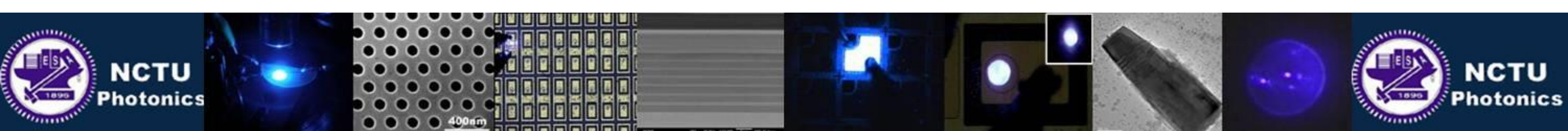
National Chiao-Tung University (NCTU)

IEEE senior member IET Fellow SPIE Fellow and OSA Fellow







Prof. Hao-chung Kuo CV

IEEE senior member IET Fellow SPIE Fellow and OSA Fellow

1990 NTU Physics (under Prof. YF Chen special project on Semiconductor)
1995 MS in Rutgers University (NJ) 1998 UIUC Ph.D. in ECE/Applied Physics

08/02- now, Distinguished Professor*, National Chiao-Tung University,*
Associate Dean, office of International office;
Associate Director, Photonics Center, NCTU

02/10-08/12 TD director, TSMC

12/05-02/10 Consultant,
Epistar Corporation

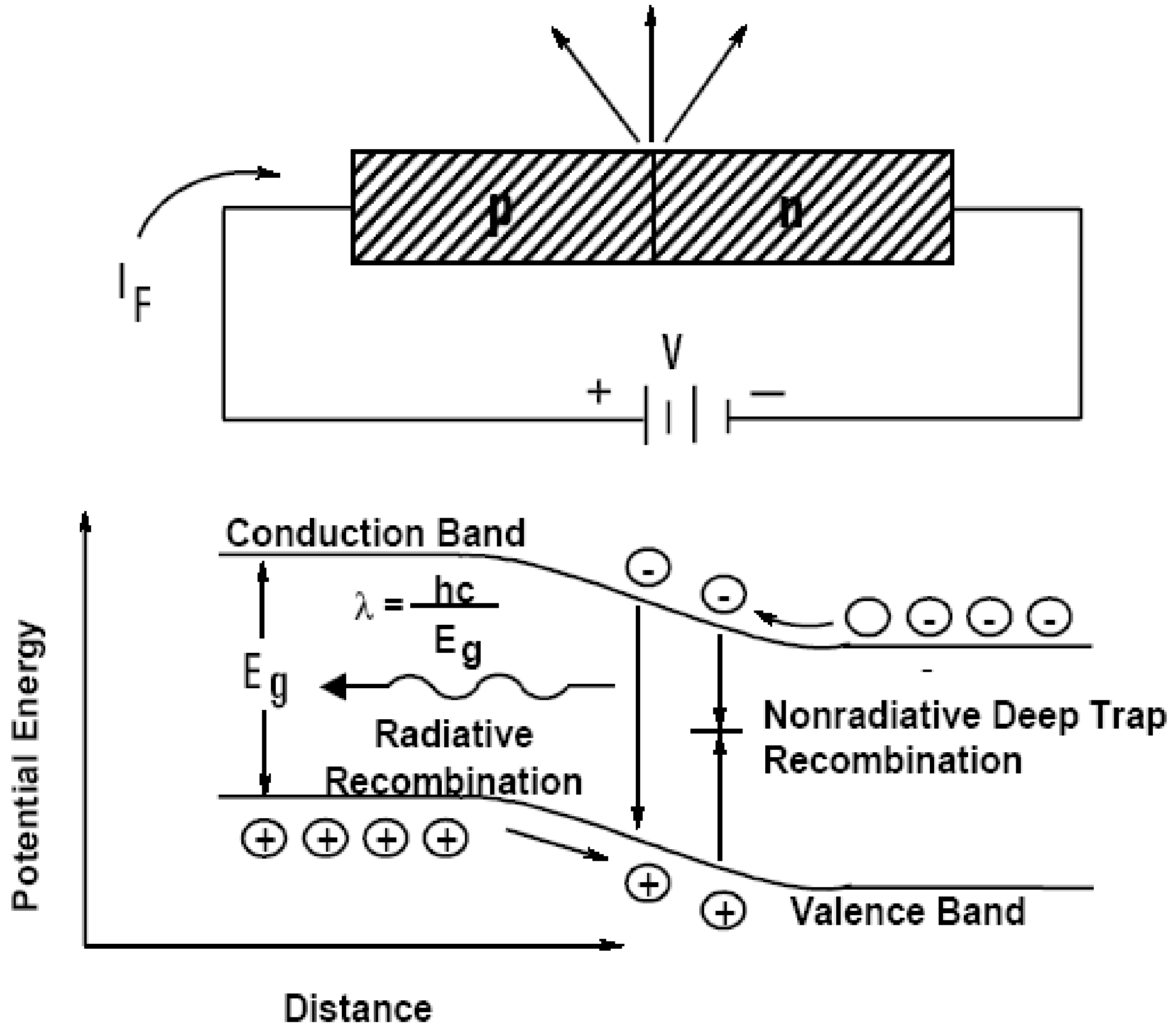
02/2002-now Advisor, ITRI,

06/2009-12/2009 Technical Director and Visiting Professor,
LED and Solar cell program, Nano and advanced material Institute, HKUST

06/2005-12/2005*,* ***Senior Manager and Visiting Professor, HK ASTRI***

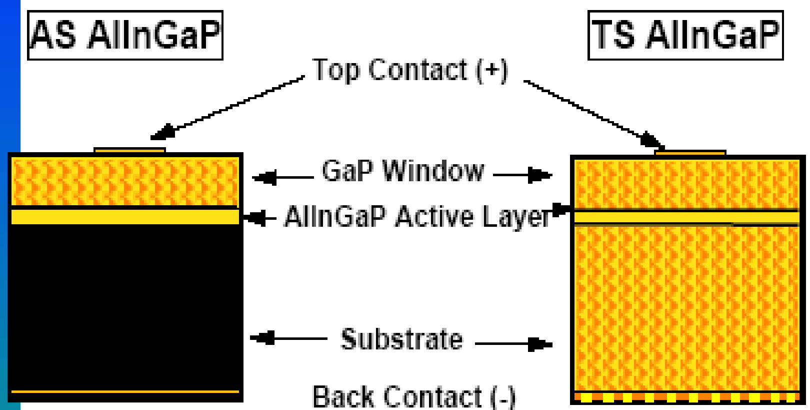
2000-2002 Engineer Manager (Epitaxy)*, LuxNet Corp, Fremont, CA.*
1999-2000 Senior R&D Scientist*, Agilent Technologies, CA*
1993-1995 Bell Lab Lucent /AT&T

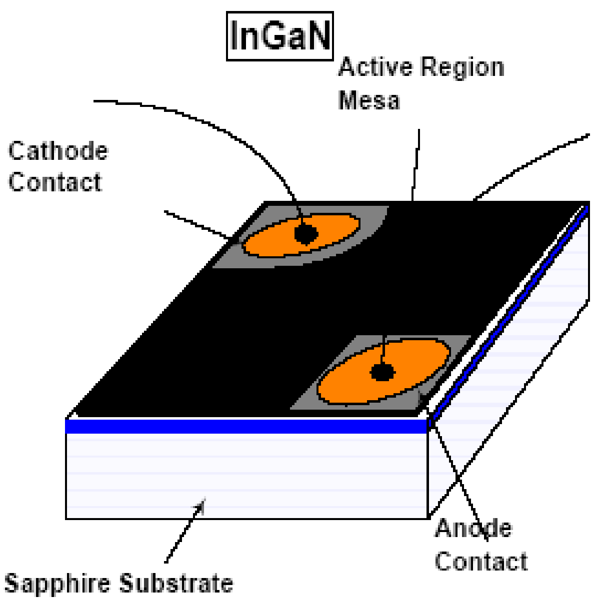
Light-Emitting Diode Structure



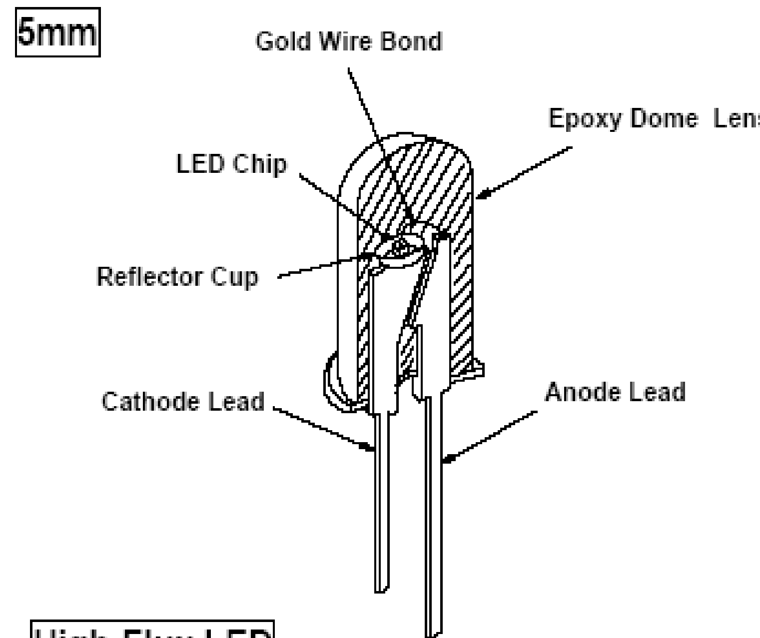
What is an LED?

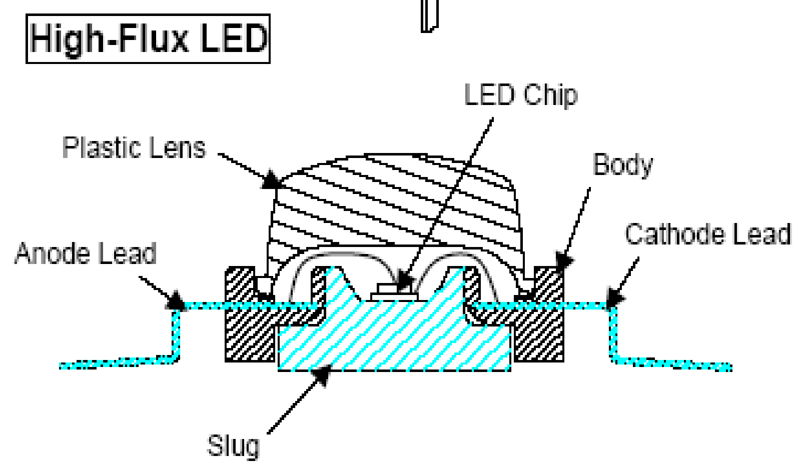
Semiconductor chip



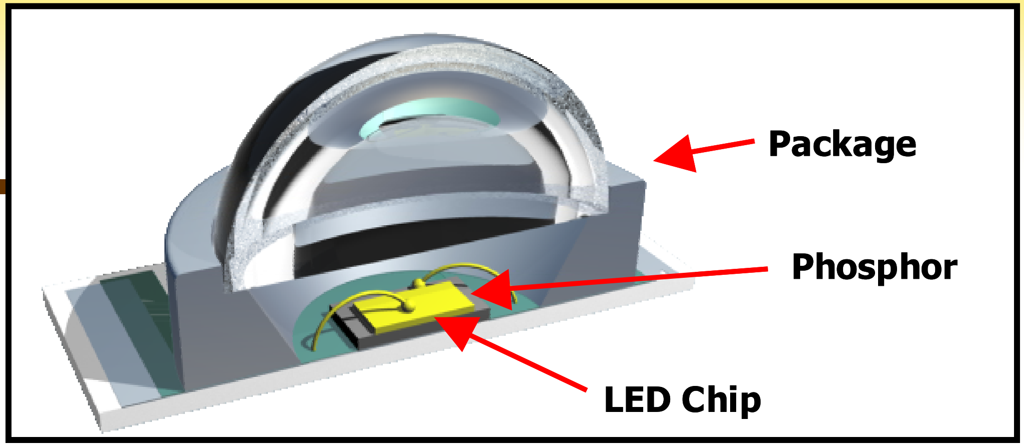


Package





LED Technology



LED Chip

- Determines raw brightness and efficacy

Phosphor system

- Determines color point and color point stability

Package

- Protects the chip and phosphor
- Helps with light and heat extraction
- Primary in determining LED lifetime

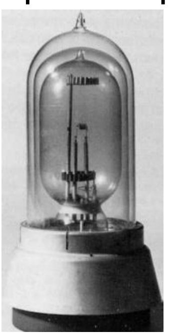
…A Brief History of Lighting

1879
Edison Light Bulb

U.S. 223,898

1901
Fluorescent Tube

1919
Sodium Vapor Lamp



1970s
First Red LED

Calculators and Indicators

~1990
"High Brightness" Red, Orange, Yellow, & Green LEDs

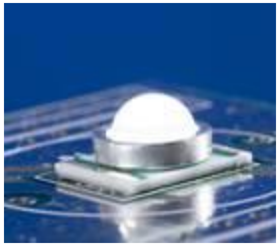
Monochrome signs

1995
"High Brightness" Blue, Green LEDs

Full Color Signs

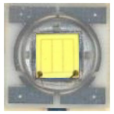
2000
White LED Lamp demonstrates Incandescent Efficacy (17 lm/W)

2005
White LED Lamp demonstrates Fluorescent Efficacy (70 lm/W)



Solid State Lighting

2009
Production White LED Lamp Exceeds 100 lm/W



- **Current lighting technology is over 120 years old**
- **LEDs began as just indicators, but are now poised to become the most efficient light source ever created**

A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

1907 H. Round

Fig. 1. Publication reporting on a "curious phenomenon", namely the first observation of electroluminescence from a SiC (carborundum) light-emitting diode. The article indicates that the first LED was a Schottky diode rather than a pn-junction diode (after H. J. Round, *Electrical World* Vol. **49**, p. 309, 1907)

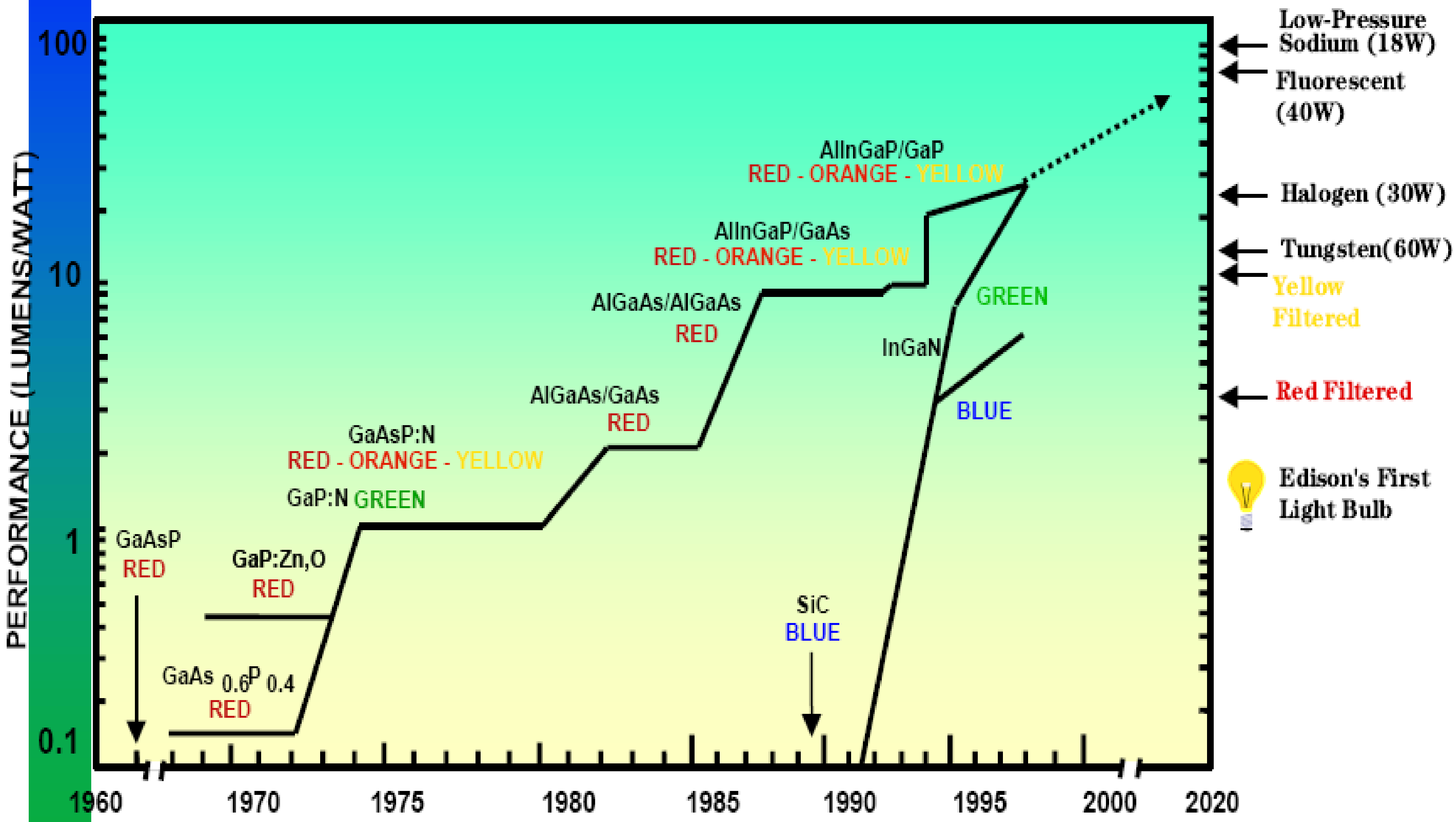
No Efficient Blue LED till 1990

History: Light Emitting Diode (LED)

Discovered in 1907 and ignored until…

- 1962 – first visible-spectrum LED
- 1972 – first yellow and high-output red LEDs
- 1977 – first flat panel LED screen
- → 1993 – high brightness blue LED
- 1995 – white LED
- 1999 – high-power (≥ 1 watt) LED
- 2003 – LED = 4 times incandescent efficiency
- 2006 – LED = 8 times incandescent efficiency

Evolution of the Visible-Spectrum Light-Emitting Diode



Breakthrough in blue, green and white LEDs

First true p-type doping in GaN-Mg activated by electron beam irridiation

-H. Amano et al, Jpn. J. Appl. Phys. 28, L2112 (Dec 1989)

P-GaN by high temperature annealing

Nobel Prize cite paper

-S. Nakamura et al, US Pat 5,306,662 (1994).

First p-n junction GaN LED

-I Akasaki et al, Inst. Phys. Conf. Ser. 129, 851 (1992).

First InGaN double heterostructure blue and green LEDs

-S. Nakamura et al, Jpn. J. Appl. Phys. 32, L8 (1993). Appl. Phys. Lett, 62, 2390 (1993).

TG and Nichia start patent war

Brief History of LEDs

- 1955 – RCA reports IR emission using GaAs
- 1961 – TI gets patent for IR LED
- 1962 – GE develops first visible LED (Holonyak)
- 1968 – Monsanto develops first commercially available LEDs for HP35 calculator
- 1970's - GaP-based red, green and yellow
- 1980's – AlGaAs/AlInGaP red and amber LEDs
- 1990's – InGaN LEDs and YaG phosphor – Nakamura, Akasaki,Amano
- 2000's – White LEDs for SSL

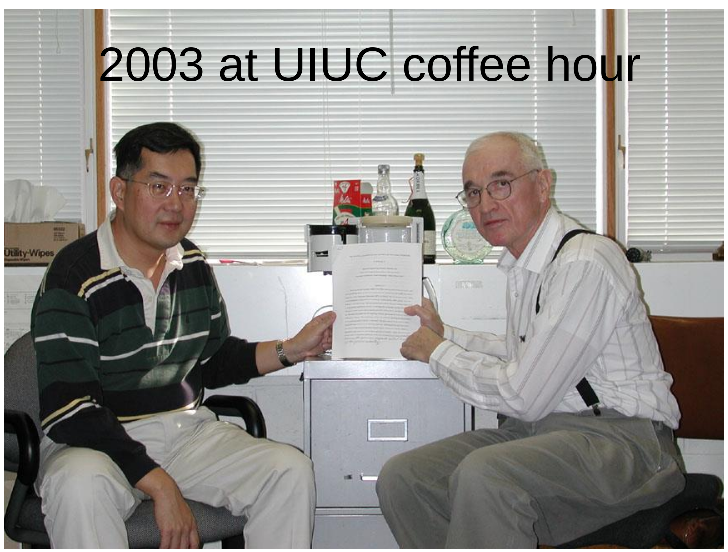
2007 at UIUC microelectronic lab

Special thanks to

My advisor Prof. Greg Stillman for C-doped HBT

And my Advisor's Advisor

Prof. Nick Holonyak Jr -Father of visible LED, O-VCSEL



2003 at UIUC coffee hour

2012 at UIUC LED 50th

Prof. Holonyak Invention

Inventions [edit]

In addition to introducing the III-V alloy LED, Holonyak holds 41 patents. His other inventions include the red-light semiconductor laser, usually called the laser diode (used in CD and DVD players and cell phones) and the shorted emitter p-n-p-n switch (used in light dimmers and power tools).[4]

In 2006, the American Institute of Physics decided on the five most important papers in each of its journals since it was founded 75 years ago. Two of these five papers, in the journal *Applied Physics Letters*, were co-authored by Holonyak. The first one, coauthored with S. F. Bevacqua in 1962, announced the creation of the first visible-light LED. The second, co-authored primarily with Milton Feng in 2005, announced the creation of a transistor laser that can operate at room temperatures. Holonyak predicted that his LEDs would replace the incandescent light bulb of Thomas Edison in the February 1963 issue of *Reader's Digest*,[5] and as LEDs improve in quality and efficiency they are gradually replacing incandescents as the bulb of choice.

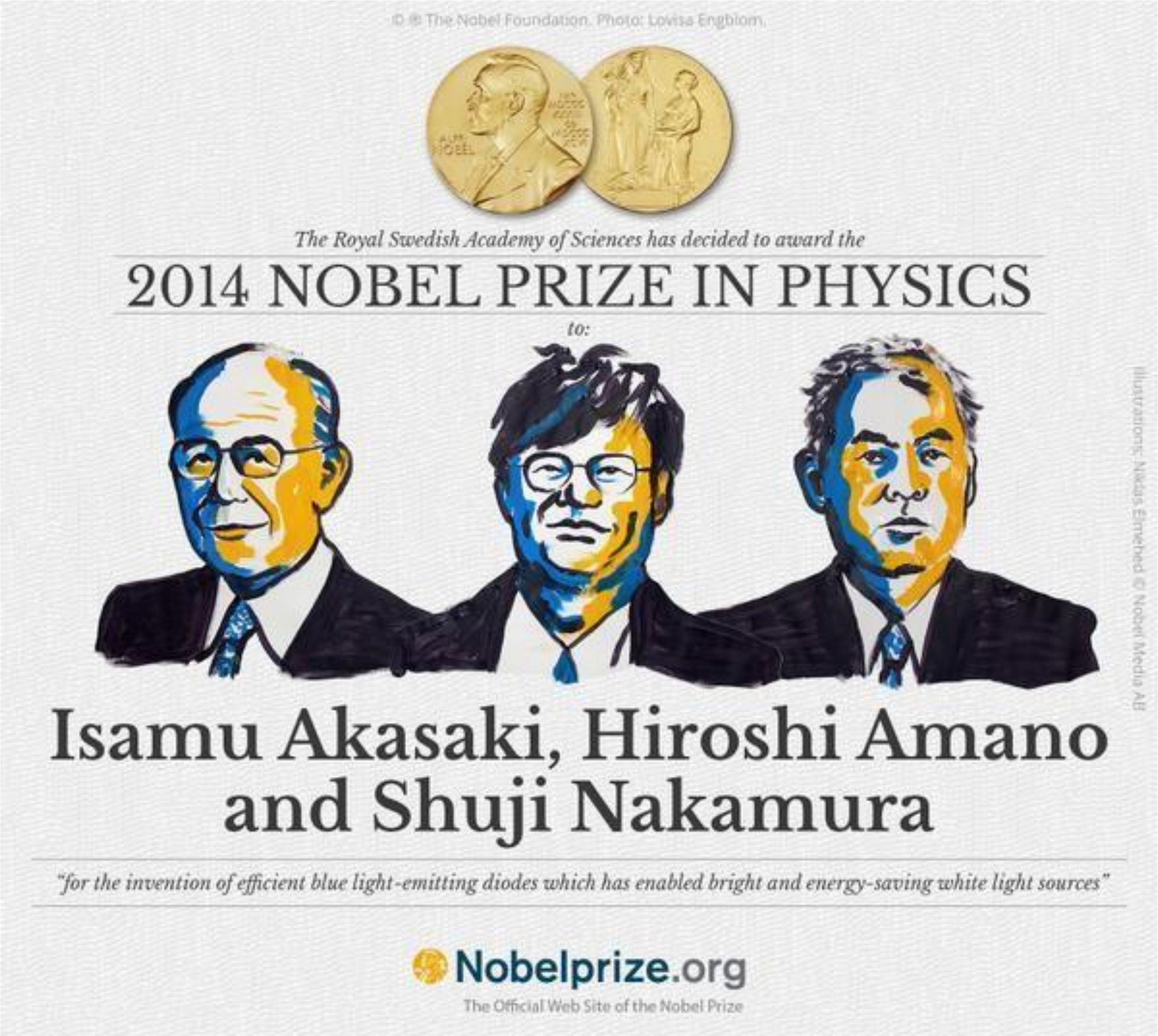
Born	November 3, 1928 (age 85) Zeigler, Illinois, U.S.
Residence	United States
Nationality	American
Fields	Electrical engineering
Alma mater	University of Illinois at Urbana-Champaign; BS 1950, MS 1951, PhD 1954
Doctoral advisor	John Bardeen
Notable awards	National Academy of Engineering (1973) National Academy of Sciences, IEEE Edison Medal (1989) National Medal of Science (1990) National Medal of Technology (2002) IEEE Medal of Honor (2003) Lemelson-MIT Prize (2004) National Inventors Hall of Fame (2008)

Prof. John Bardeen

Prof. John Bardeen

Died	January 30, 1991 (aged 82) Boston, Massachusetts, U.S.
Residence	United States
Nationality	American
Fields	Physics
Institutions	Bell Telephone Laboratories University of Illinois
Alma mater	University of Wisconsin–Madison Princeton University
Doctoral advisor	Eugene Wigner *
Doctoral students	John Robert Schrieffer* Nick Holonyak
Known for	Transistor BCS theory Superconductivity
Notable awards	Stuart Ballantine Medal (1952) Oliver E. Buckley Condensed Matter Prize (1954) * Nobel Prize in Physics (1956) National Medal of Science (1965) IEEE Medal of Honor (1971) * Nobel Prize in Physics (1972) Lomonosov Gold Medal (1987) Harold Pender Award (1988)

2014 the Nobel Prize in Physics Awarded



2014 the Nobel Prize in Physics Awarded to Isamu Akasaki

Brief Bio:

Isamu Akasaki (赤崎 勇) was born in Kagoshima, Japan. Dr. Akasaki graduated from Kyoto University in 1952, and obtained a Ph.D degree in Electronics from Nagoya University in 1964. He started working on GaN-based blue LEDs in the late 1960s. Step by step, he improved the quality of GaN crystals and device structures at Matsushita Research Institute Tokyo,Inc.(MRIT), where he decided to adopt metalorganic vapour phase epitaxy (MOVPE) as the preferred growth method for GaN.

Important Contribution:

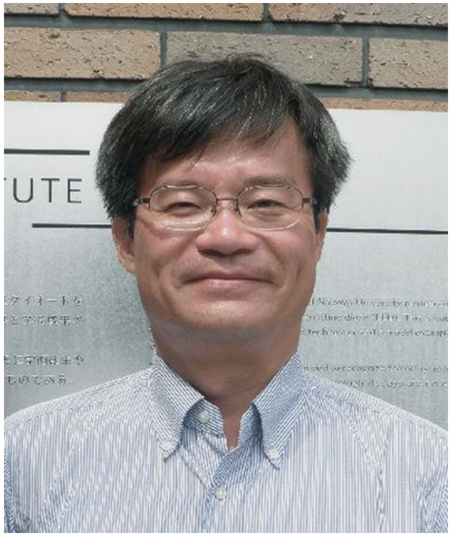
In 1981, he started afresh growth of GaN by MOVPE at Nagoya University, and in 1985 he and his group succeeded in **growing high-quality GaN on sapphire substrate by pioneering the low-temperature (LT) buffer layer technology**.

This high-quality GaN enabled them to discover p-type GaN by doping with magnesium (Mg) and subsequent activation by electron irradiation (1989), to **produce the first GaN p-n junction blue/UV LED** (1989), and to achieve conductivity control of n-type GaN (1990) and related alloys (1991) by doping with silicon (Si), enabling the use of heterostructures and multiple quantum wells in the design of more efficient p-n junction light emitting structures. He also verified **quantum size effect** (1991) and **quantum confined Stark effect** (1997) in nitride system, and in 2000 showed theoretically the **orientation dependence of piezoelectric field** and the **existence of non-/semi-polar GaN crystals**, which have triggered today's world-wide efforts to grow those crystals for application to more efficient light emitters.

2014 the Nobel Prize in Physics Awarded to Hiroshi Amano

Brief Bio:

Hiroshi Amano (天野 浩) was born in Hamamatsu, Japan. He received his BE, ME and DE degree in 1983, 1985 and 1989, respectively, from Nagoya University. He joined Professor Isamu Akasaki's group in 1982 as an undergraduate student. Since then, he has been doing research on the growth, characterization and device applications of group III nitride semiconductors. He is the first one who demonstrated growing p-typr GaN and fabrication a p-n junction GaN LED in the world.



Important Contribution:

In 1985, he **developed low-temperature deposited buffer layers** for the growth of group III nitride semiconductor films on a sapphire substrate, which led to the realization of group-III-nitride semiconductor based light-emitting diodes and laser diodes. In 1989, he **succeeded in growing p-type GaN** and fabricating a **p-n-junction GaN-based UV/blue light-emitting diode for the first time in the world**.

2014 the Nobel Prize in Physics Awarded to Shuji Nakamura

Brief Bio:

Shuji Nakamura (中村 修二) was born in Ikata, Japan. He graduated from the University of Tokushima in 1977 with a BS degree in electronic engineering, and obtained an MS degree in 1979. It was while working for Nichia that Nakamura invented the first high brightness gallium nitride (GaN) LED whose brilliant blue light, when partially converted to yellow by a phosphor coating, is the key to white LED lighting, which went into production in 1993. He was awarded a Ph.D degree from the University of Tokushima in 1994 and took a position as a professor of engineering at the University of California, Santa Barbara.

Important Contribution:

Previously, J. I. Pankove and co-workers at RCA put in considerable effort, but did not manage to make a marketable GaN LED in the 1960s. The principal problem was the **difficulty of making strongly p-type GaN**. Nakamura and his co-workers worked out the physics and pointed out the culprit was hydrogen, which passivated acceptors in GaN. **He managed to develop a thermal annealing method and obtained controlled conductivity of p-GaN**. He invented **two-flow MOCVD growth method for InGaN**, and hence to obtain **high brightness blue/UV LED** in 1993. He also demonstrate **pulse emission of InGaN/GaN blue laser diode at room temperature**, opening a way to obtain blue ray emission head for optical communication. His most important contribution of high brightness blue LED leads him to be called as the "**father of blue LED**".

Related News

https://www.youtube.com/watch?v=J-oBvPYx1NQ

https://www.youtube.com/watch?v=iMNTLDfqCvU

https://www.youtube.com/watch?v=9in3hZreYts

Photo with Prof. Nakamura
Prof. HC Kuo

2015 year of Light

All Nobel Prizes in Physics

The Nobel Prize in Physics has been awarded 108 times to 199 Nobel Laureates between 1901 and 2014. John Bardeen is the only Nobel Laureate who has been awarded the Nobel Prize in Physics twice, in 1956 and 1972. This means that a total of 198 individuals have received the Nobel Prize in Physics. Click on the links to get more information.

The Nobel Prize in Physics 2014

Isamu Akasaki, **Hiroshi Amano** and **Shuji Nakamura**

"for the invention of efficient **blue light-emitting diodes** which has enabled bright and energy-saving white light sources"

The Nobel Prize in Physics 2010

Andre Geim and **Konstantin Novoselov**

"for groundbreaking experiments regarding the two-dimensional material **graphene**"

The Nobel Prize in Physics 2009

Charles Kuen Kao

"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"

Willard S. Boyle and **George E. Smith**

"for the invention of an imaging semiconductor circuit - the CCD sensor"

Semiconductor laser/laser Physics

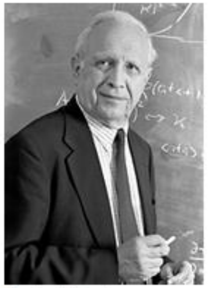


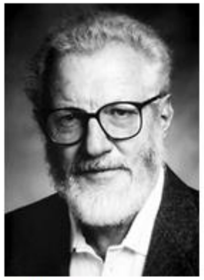
Photo: J.Reed


Photo: Sears.P.Studio


Photo: F.M. Schmidt

The Nobel Prize in Physics 2005
Roy J. Glauber
"for his contribution to the quantum theory of optical coherence"
John L. Hall and **Theodor W. Hänsch**
"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique“

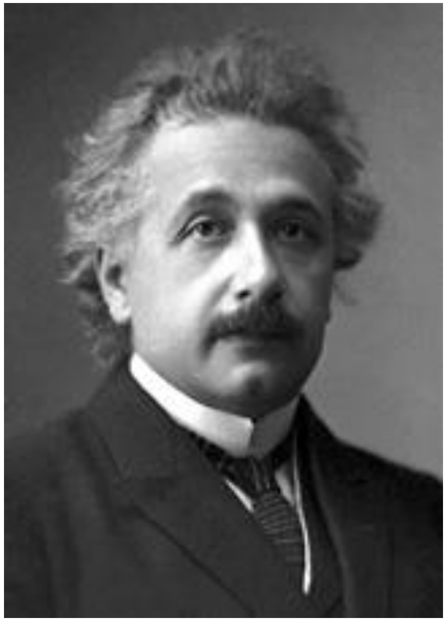

Zhores I. Alferov
Prize share: 1/4


Herbert Kroemer
Prize share: 1/4


Jack S. Kilby
Prize share: 1/2

The Nobel Prize in Physics 2000
"for basic work on information and communication technology"
Zhores I. Alferov and **Herbert Kroemer**
"for developing semiconductor heterostructures used in high-speed- and opto-electronics"
Jack S. Kilby
"for his part in the invention of the integrated circuit"

The Photoelectric Effect



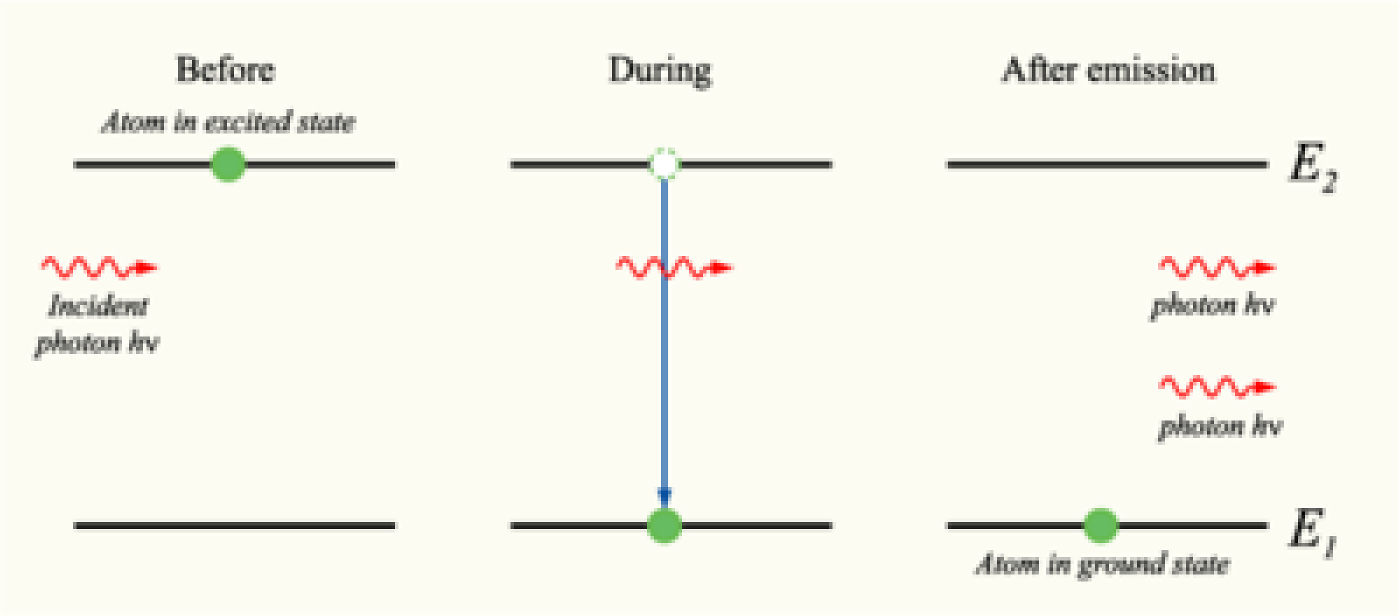
The Photoelectric Effect

Using his theory of quanta, Einstein explained the photoelectric effect. He showed that when quanta of light energy strikes atoms in the metal, the quanta force the atoms to release electrons.

Einstein's work helped justify the quantum theory. The photoelectric cell resulted from Einstein's work. This device made possible sound motion pictures, television and many other inventions. Einstein received the 1921 Nobel Prize in physics for his paper on quanta.

The work of Planck and Einstein quickly established the Quantum Theory, not only in light but also in many forms of energy. The quantum physics was born.

Photon



LED Benefits (Diode)

- *Lower cost of ownership* - Energy savings
  - Maintenance savings
- *Reliability/Ruggedness*
- *Safety* - Low voltage & Low heat generation
- *Small and light* - Flexible for styling, unique spaces
- *Dimmable, flashable, and instant turn on*
- *Excellent for distributed light*
- *Excellent control of light directionality*
  - Minimize light pollution

Effects of Mercury on the Environment

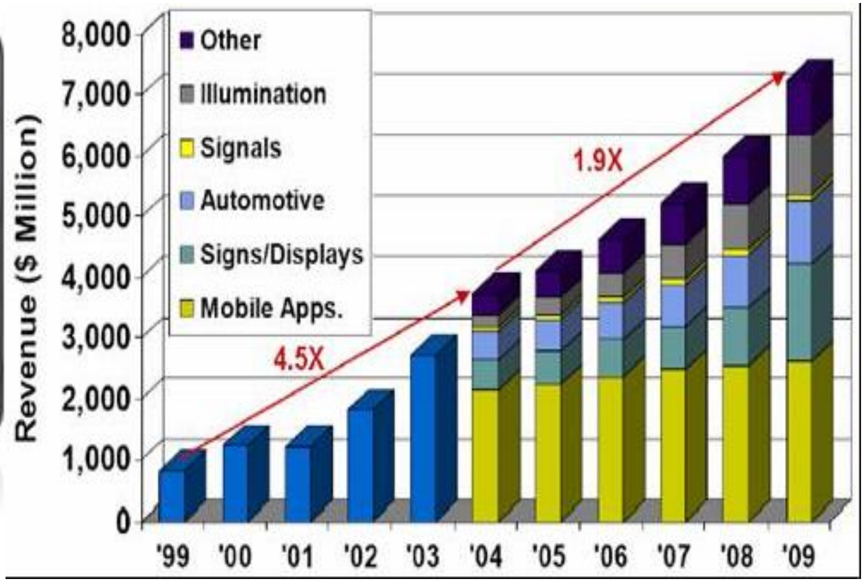
One teaspoon of mercury can contaminate a 20 acre lake. Forever.*

Each year, an estimated 600 million fluorescent lamps are disposed of in U.S. landfills amounting to 30,000 pounds of mercury waste.*

The mercury from one fluorescent bulb can pollute 6,000 gallons of water beyond safe drinking levels.*

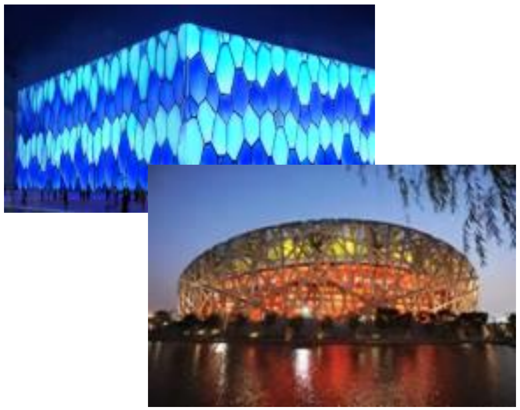
* www.lightbulbrecycling.com

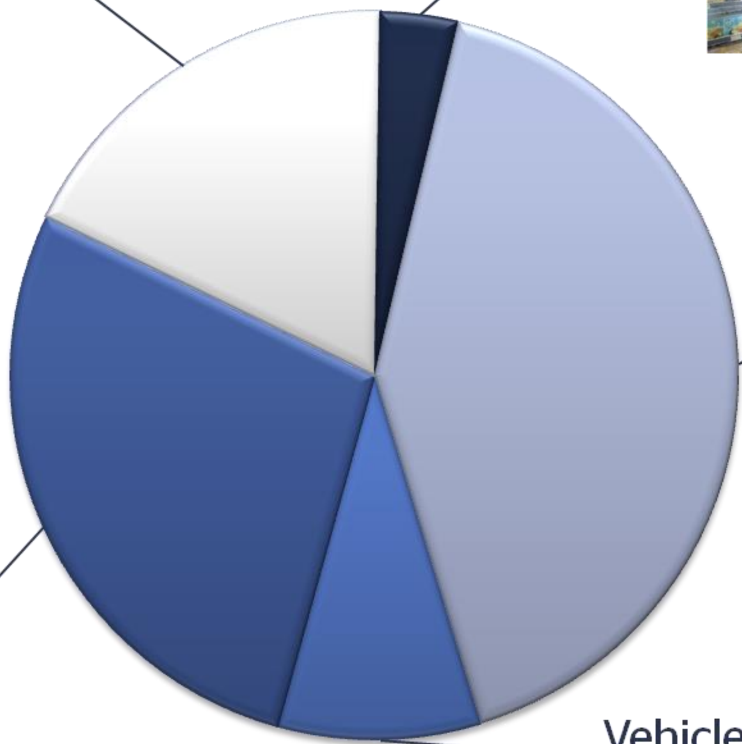
LED Applications



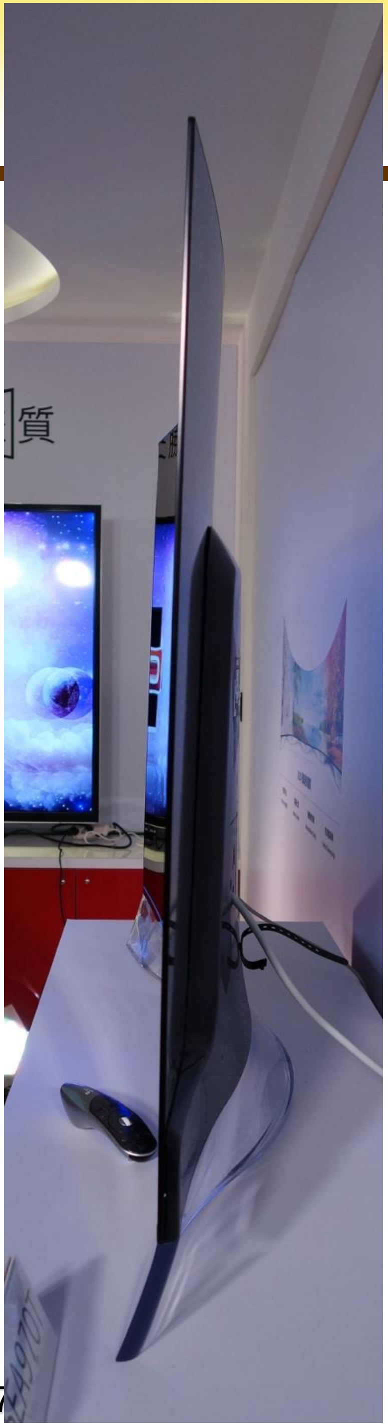
- Traffic light
- Mobile phone, notebook-BLU (100%)
  LED TV BLU (100% by 2014) flash lamp
- Outdoor full color display (100%)
- Automotive lighting-break light, daytime running lamps, turn signal, etc.
- SSL ~15-20 % lm/$?

Current LED Lighting Applications



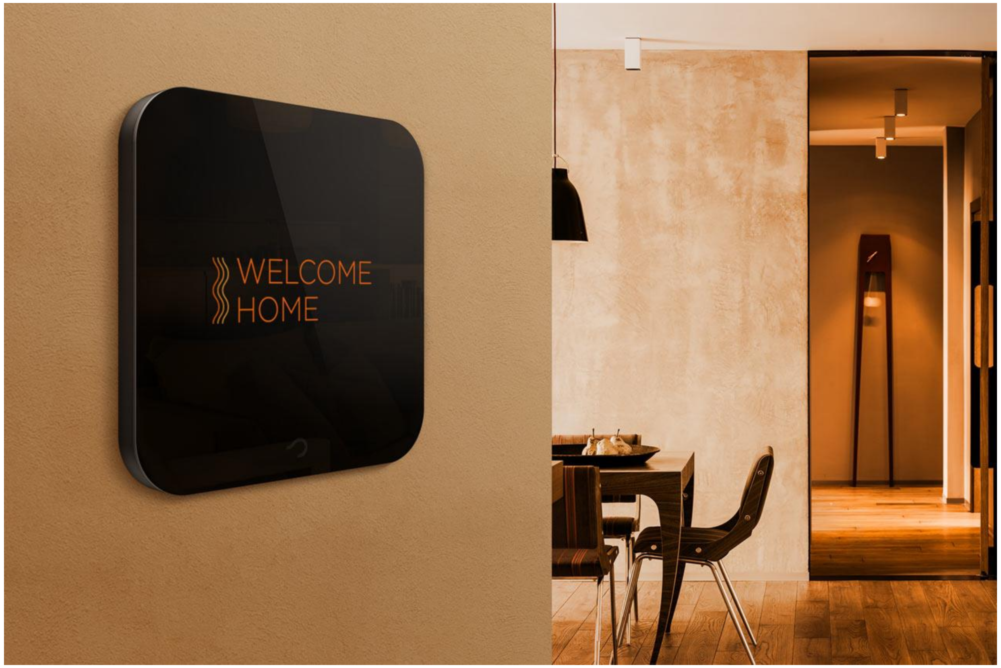


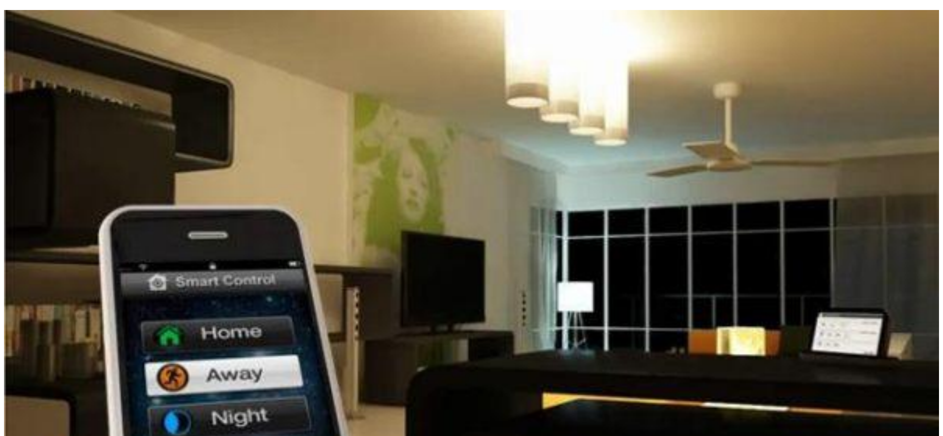
- Lumens
- LPW
- Lumens/$



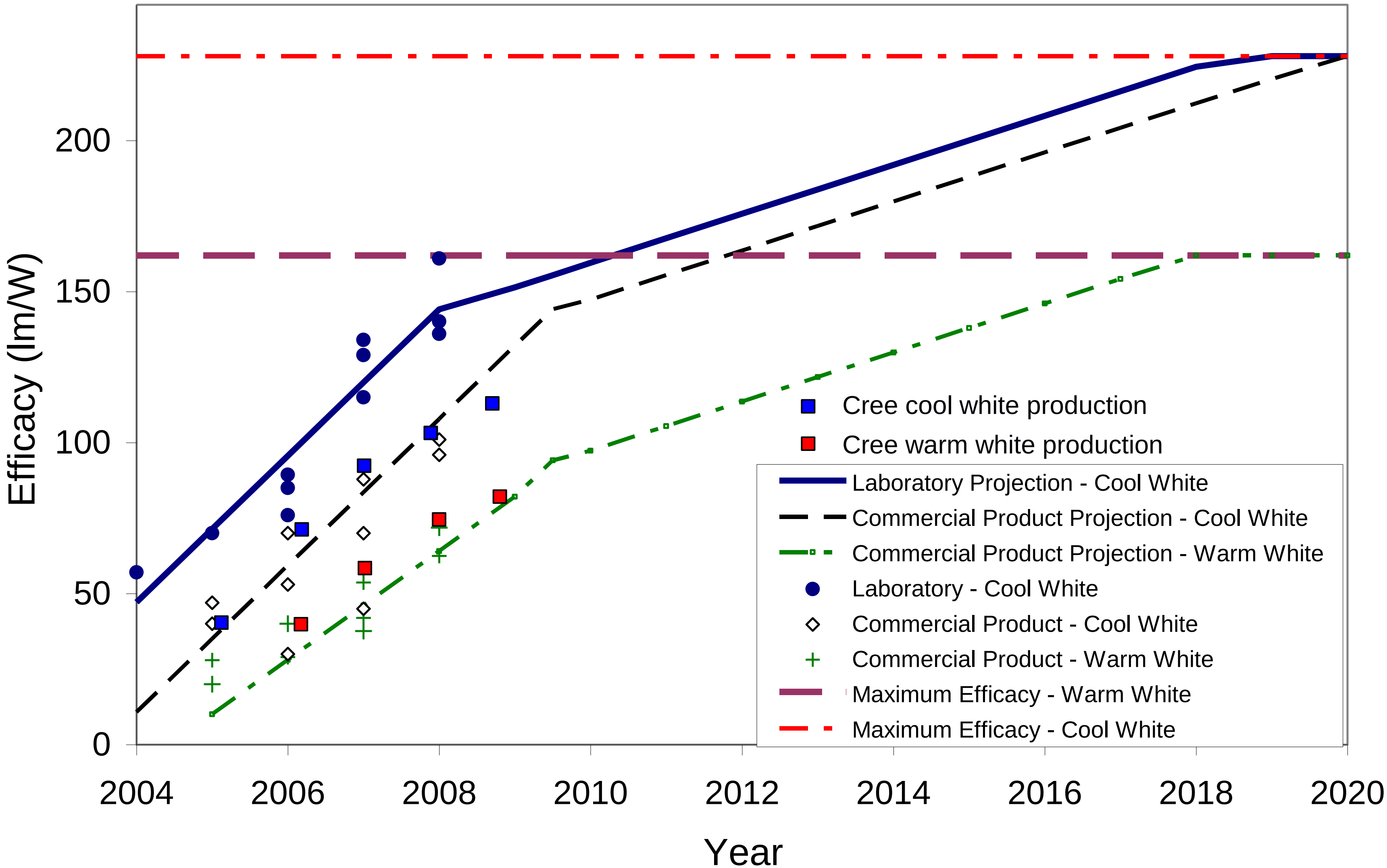
4K2K LCD with LED
Slim <1cm

Smart Lighting -everywhere



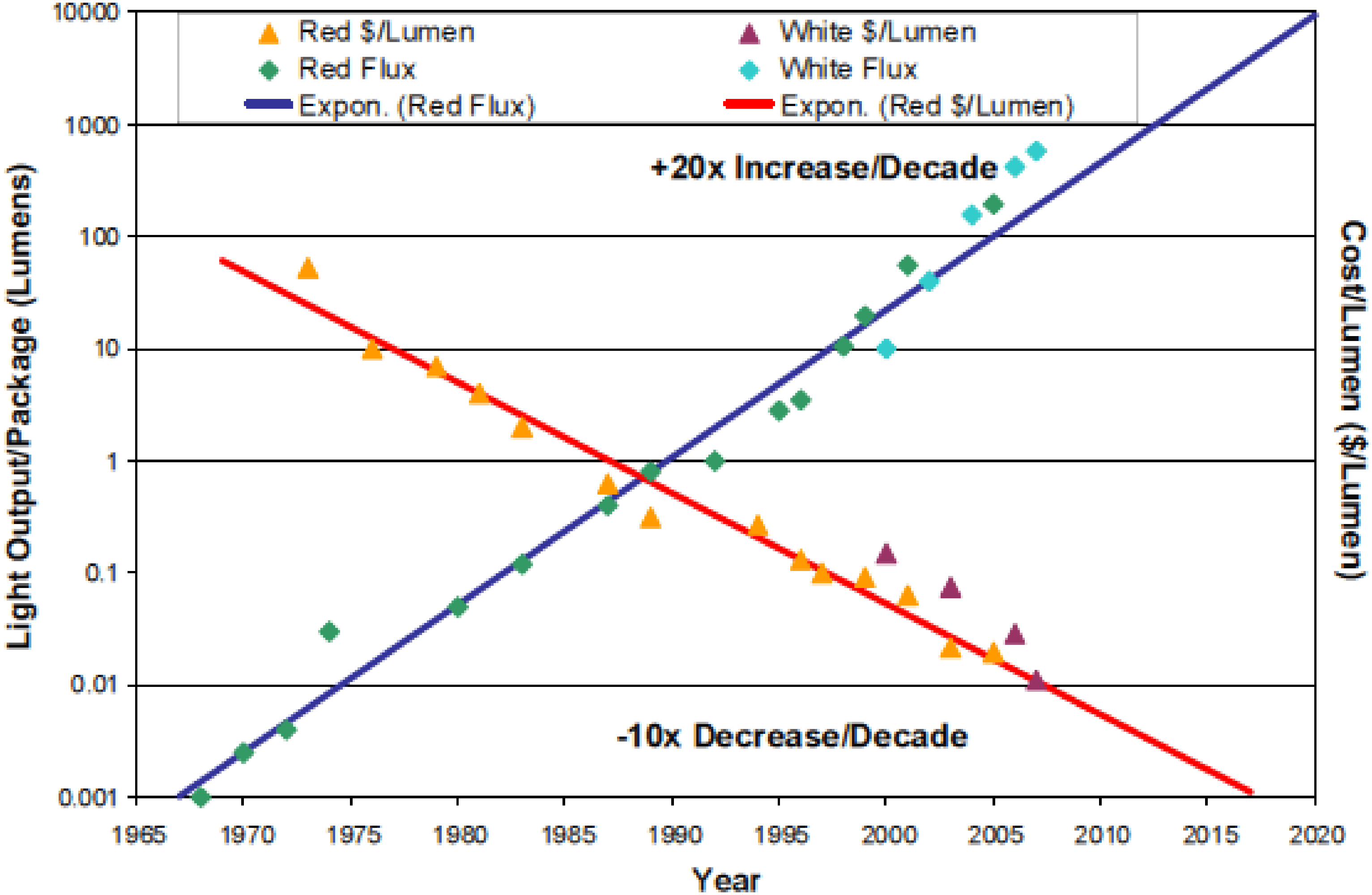


DOE Roadmap 150 lm/W (lab >200 lm/W)



US Department of Energy 2009 Multi-Year Plan for SSL

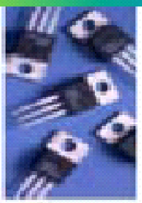
Haitz's Law



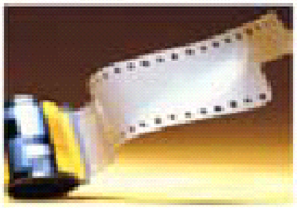
Red $/Lumen
White $/Lumen
Red Flux
White Flux
Expon. (Red Flux)
Expon. (Red $/Lumen)
+20x Increase/Decade
-10x Decrease/Decade
Light Output/Package (Lumens)
Cost/Lumen ($/Lumen)
Year
10000
1000
100
10
1
0.1
0.01
0.001
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020

History of Success for Solid State Technology

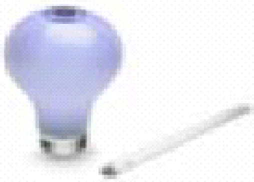
Vacuum Tubes → Transistors (1940s – 1950s)



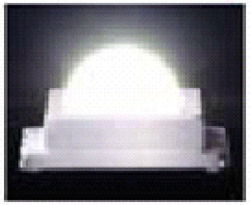
CRT → Flat Panel (1990s – 2000s)



Film → Flash Memory (1990s – 2000s)



Light Bulbs/ Fluorescent → Solid State Lighting (2000s – ...)



Epistar corporation
晶元光電 股份有限公司

Outline

- **Challenges for Lighting Applications**
- **LED LEE efficiency**
- **Physical mechanisms-efficiency droop**
- **How to eliminate droop at c-plane LED with strong QCSE**
- **Graded-composition electron blocking layer (AlGaN)**
- **Efficiency droop in c-plane and m-plane GaN LED**
- **Semipolar {10-11} InGaN/GaN Nanopyramid LED**
- **Conclusion**

20 YEARS OF WORK ON LED

EPITAXIAL LAYER

ELECTRON-HOLE RECOMBINATION

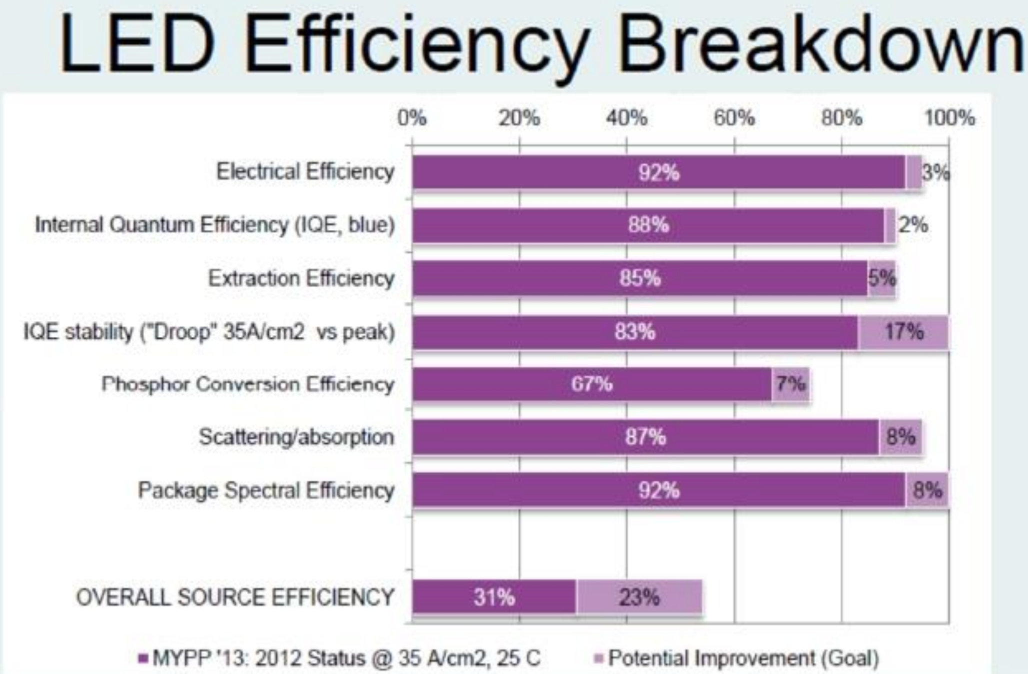
LIGHT GENERATION ACROSS JUNCTION

LIGHT EXTRACTION

PACKAGING

LED Efficiency Improvement (Blue+Phosphor)

LER (Lm/W)



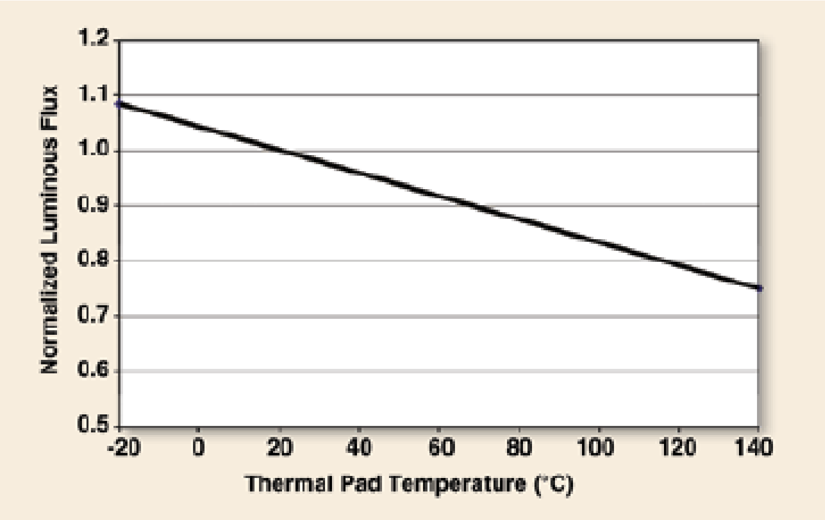
$$\eta_{LED}(Lm/W) = [IQE \times \eta_{extraction} \times \eta_{electrical}] \times \eta_{phosphor} \times \eta_{package} \times$$

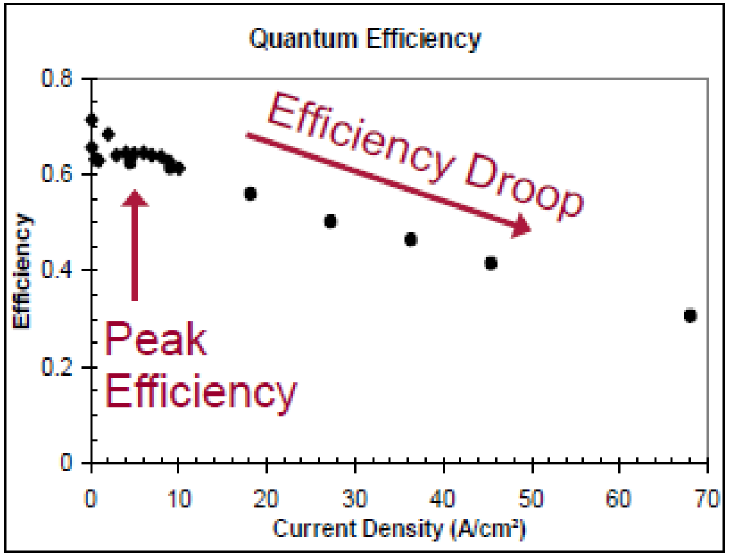
IQE (droop) ,**Vf, chip** **LEE**, **<u>Package</u>**

Sources: DOE SSL MYPP(2013)

Droop – Key for SSL

Press release (Epistar) > 200 lm/W on COG





Thermal Droop

Current Droop of Chip

Outline

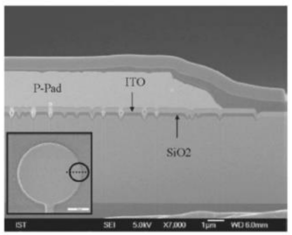
- Challenges for Lighting Applications
- LED LEE efficiency (H-die, HV LED)
- Physical mechanisms-efficiency droop
- How to eliminate droop at c-plane LED with strong QCSE
- Graded-composition electron blocking layer (AlGaN)
- Efficiency droop in c-plane and m-plane GaN LED
- Semipolar {10-11} InGaN/GaN Nanopyramid LED

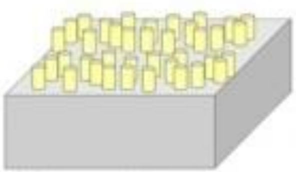
LEE in H-die (ITO) improve reach >85%
Nanotechnology transfer to Epistar (low cost)

Current spreading (NCKU)

SiO_2 current blocking layer underneath

Electrochemical and Solid-State Letters, 10 (6) H175-H177 (2007)





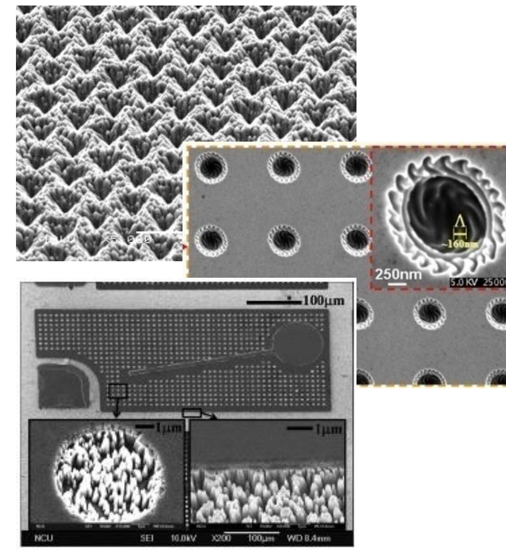
Nano surface roughness (NCKU, NCTU)

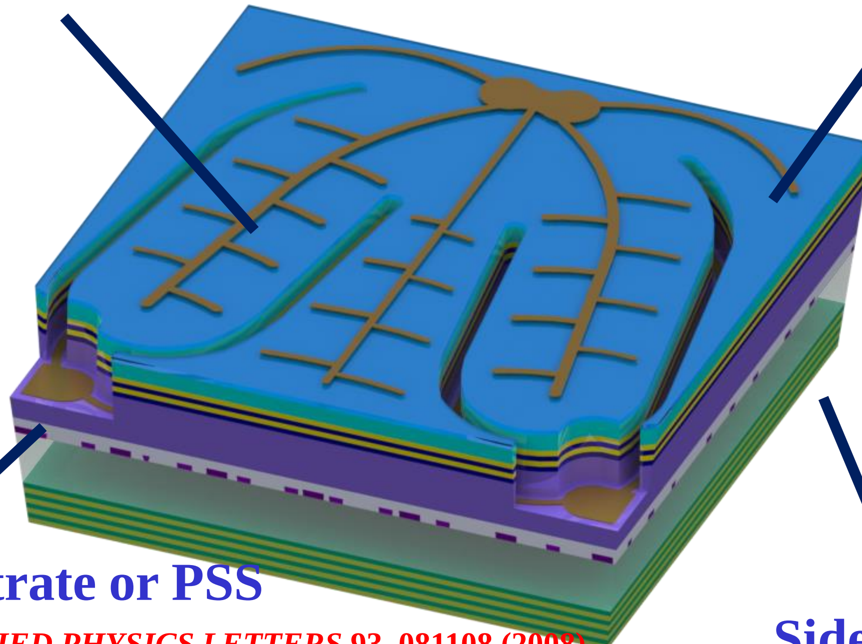
Nanotechnology, 16, 1844–1848 (2005)

OPTICS EXPRESS, Vol. 20, No. 5, (2012)

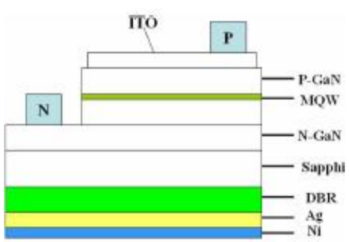
IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 21, NO. 18, (2009)

NUS





Nano-patterned substrate or PSS (NCTU/HKUST) *APPLIED PHYSICS LETTERS* 93, 081108 (2008)

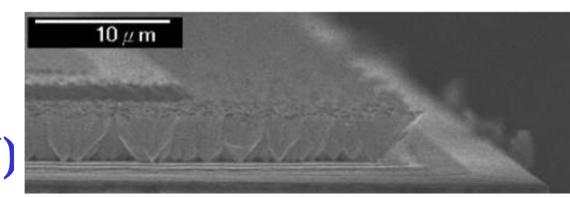


SiO_2/TiO_2 DBR back reflector (NCKU)

JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 29, NO. 7 (2011)

(NCKU)

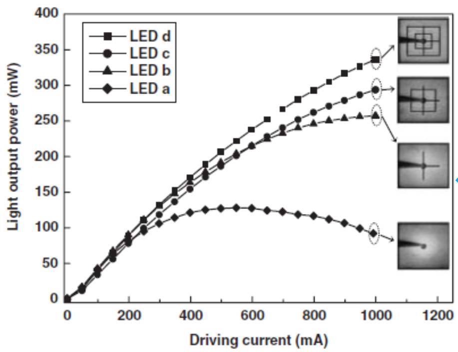
Side-wall undercut etching



IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 21, NO. 8 (2009)

Vertical LED with nanocone (NCTU/NCKU)

Electrode Patterns Design(NCTU)

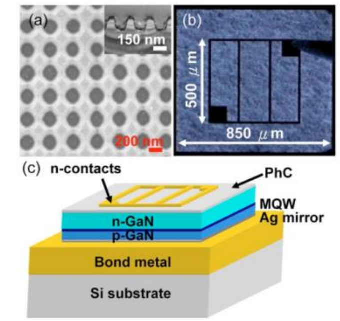


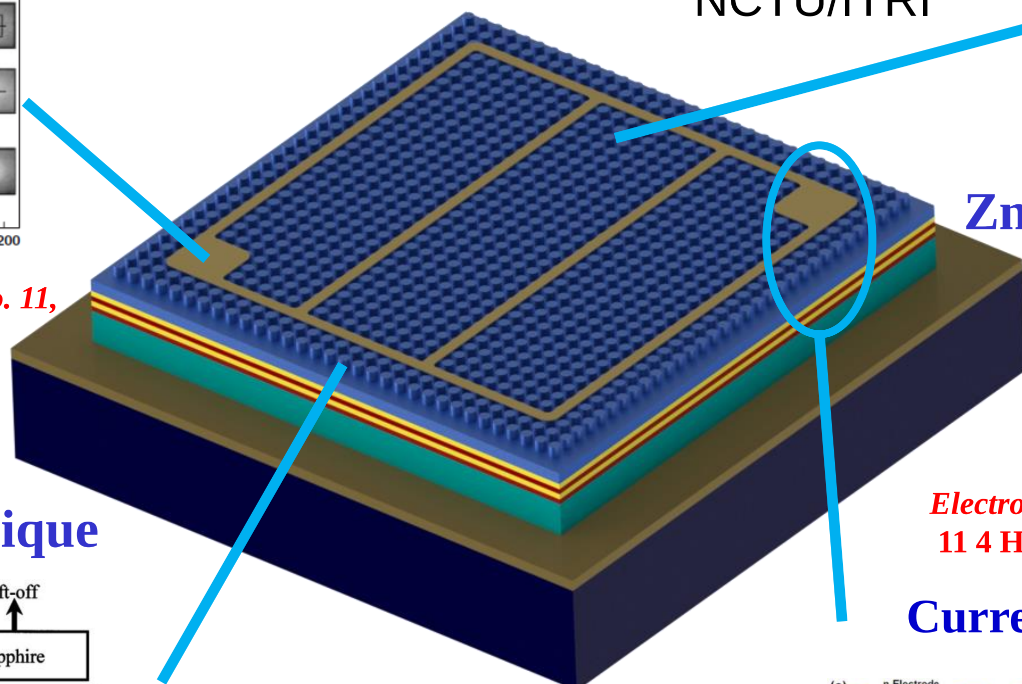
Jpn. J. of Appl. Phys., Vol. 44, No. 11, pp. 7910 –7912 , 2005

Photonic crystal structure

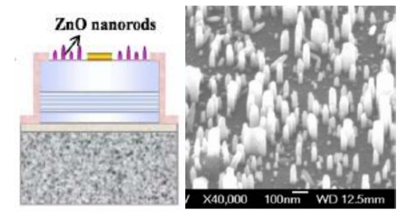
APPLIED PHYSICS LETTERS 94, 123106 (2009)

NCTU/ITRI



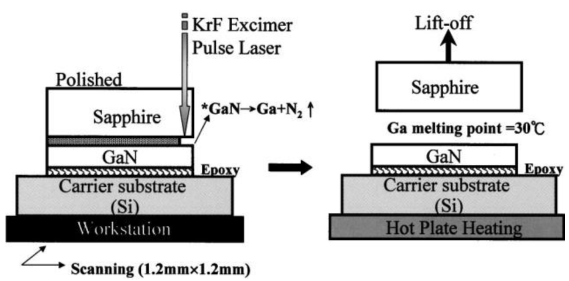


ZnO Nanorod Arrays



Electrochemical and Solid-State Letters, 11 4 H84-H87, 2008

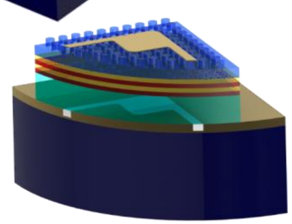
Laser lift-off technique

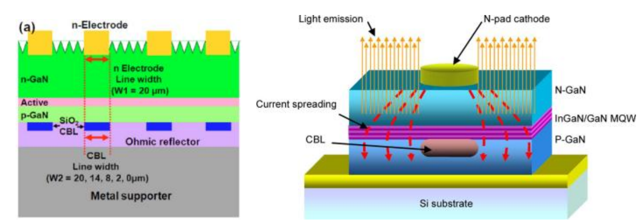


J. Appl. Phys., Vol. 95, No. 8, 15, 2004

NCTU/UCB

Current blocking layer

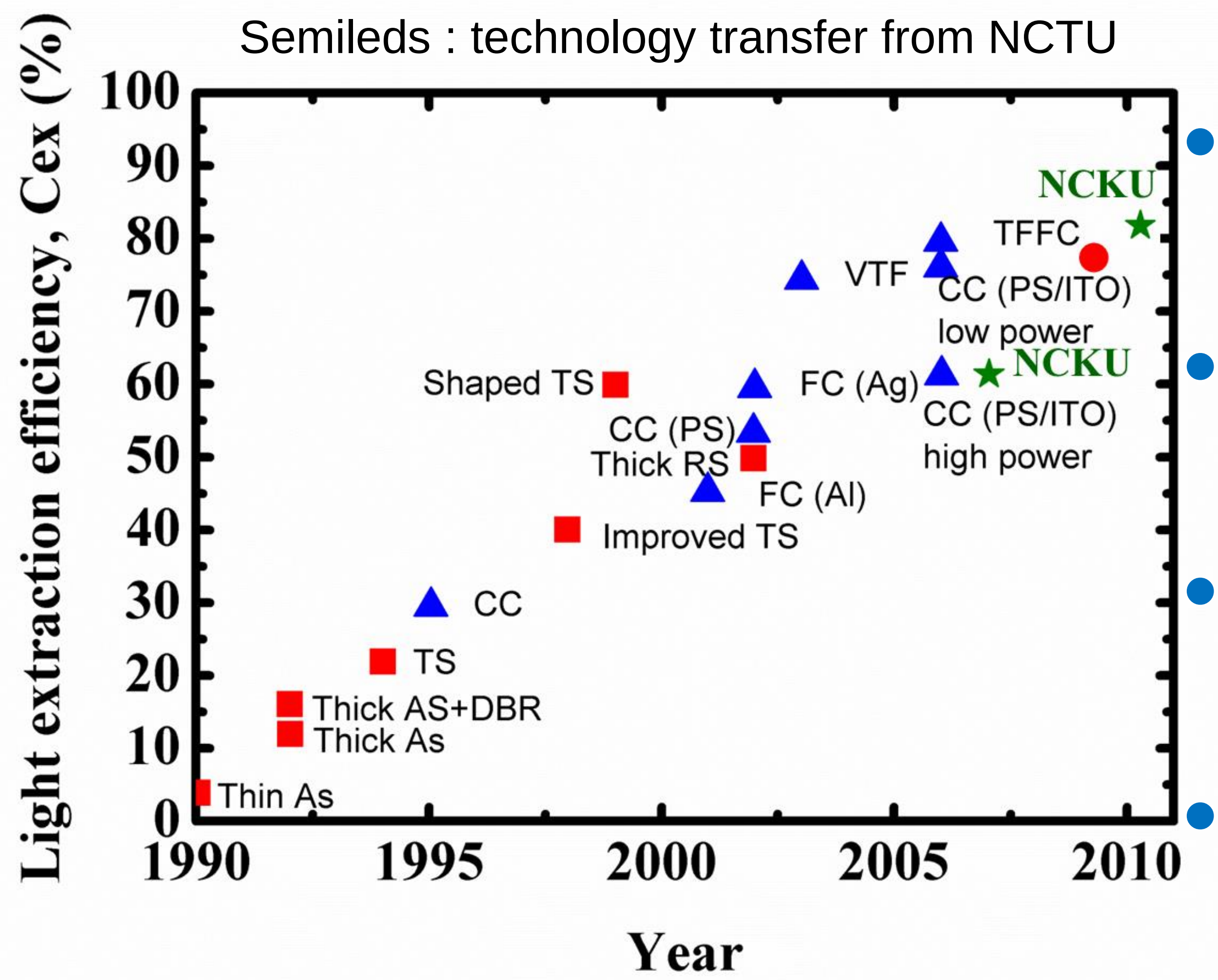




Hwan Hee Jeong et. al., ESSL, 13 7 H237, 2010

Semiled : Spin off from NCTU *IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 21, NO. 11, 2009*

Evolution of Chip (NCTU,NCKU)

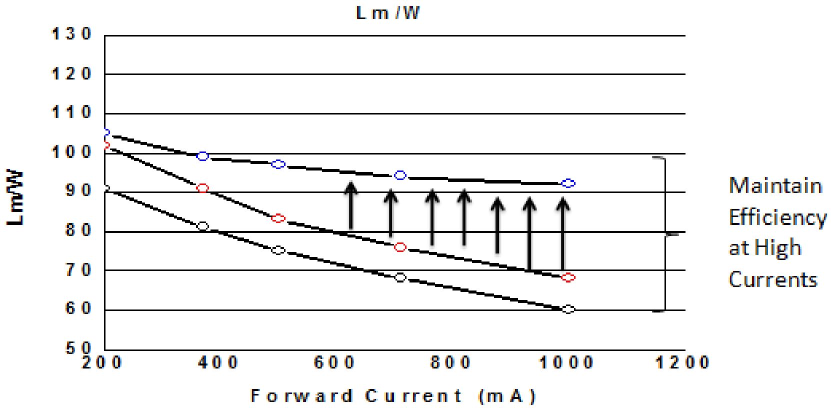


- **Al Mirror + TiO2/SiO2 DBR Backside Reflector**
  JOURNAL OF LIGHTWAVE TECHNOLOGY, **VOL. 29, NO. 7 (2011)**
- **Mesh ITO p-Contact and Nanopillars**
  IEEE PHOTONICS TECHNOLOGY LETTERS, **VOL. 21, NO. 18, (2009)**
- **Phosphoric Acid Etched Undercut Sidewalls**
  IEEE PHOTONICS TECHNOLOGY LETTERS, **VOL. 21, NO. 8, (2009)**
- **Laser-induced periodic structure**
  OPTICS EXPRESS, Vol. 20, No. 5, (2012)

- ➢ **Thin GaN LEE (Cree, Lumiled, Semileds) also >85%**
- ➢ **Novel thin GaN Target：LEE > 90%**

What Causes Efficiency Droop ?

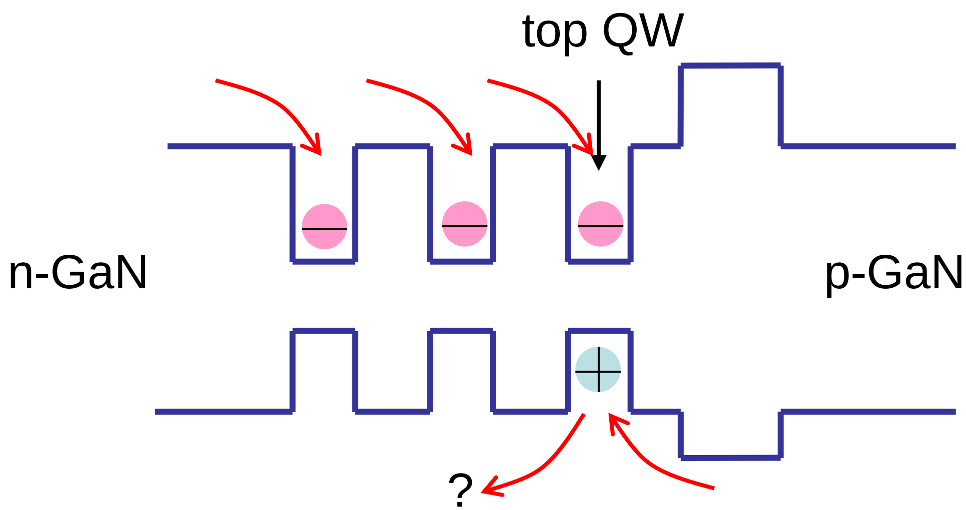
- Simple answer: We don’t know yet



- Several competing theories/explanations

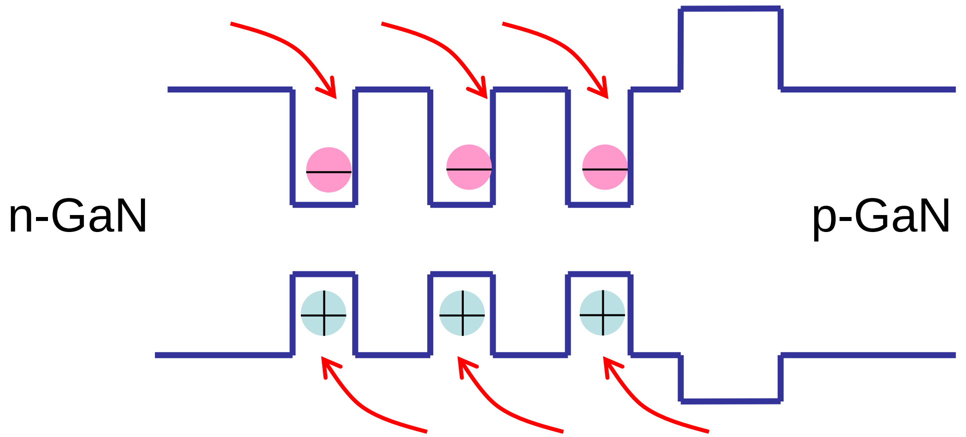
1) Electron overflow at high current densities due to inadequate electrical confinement layers (RPI, GIT)
2) Electron overflow due to polarization fields in the MQW region (Rensselaer Ploytechnic Institute)
3) Auger recombination due to high carrier density (Lumileds, UCSB) Defects assist Auger, Auger electron (UCSB)
4) Poor hole transport in MQW (Virginia Commonwealth Univ.)
5) 3D roughnesss (NTU, UCSB)

InGaN Active Regions: "MQW" ?



Electron / Hole mobility are not match
QCSE due to polarization mismatch

- **Fake MQWs**
- **Light generated only top QWs !**
- **Electron overflow is high**



- **Real MQWs**
- **Light generated in all QWs**
- **Electron overflow is reduced**
- **Vf reduced significantly**

- **Improve carrier distribution within the MQW region**

Outline

- Challenges for Lighting Applications
- LED LEE efficiency (Thin GaN, H-die, flip chip HV)
- Physical mechanisms-efficiency droop
- How to eliminate droop at c-plane LED with strong QCSE
- Graded-composition electron blocking layer (AlGaN)
- Efficiency droop in c-plane and m-plane GaN LED
- Semipolar {10-11} InGaN/GaN Nanopyramid LED

Development of Low Droop LED (NCTU, NCKU)

- **Substrate**
  - **non-polar m-plane substrate**
  - **(1-101) semi-polar GaN on Si**

  for QCSE control

  Applied Physics Letters, 2010, 96, 231101
  Applied Physics Express, 2011, 4, 012105

- **Insertion layer between MQW and n-GaN**
  - **super lattice insertion layer**

  for strain reduction

  Applied Physics Letters, 2010, 97, 251114

- **MQW design**
  - **graded-thickness MQW (GQW)**
  - **graded-composition MQB (GQB)**

  for hole transport

  Semiconductor Today, *Applied Physics Letters*, 2010, 97, 181101
  Semiconductor Today, *Applied Physics Letters*, 2011, 99, 171106

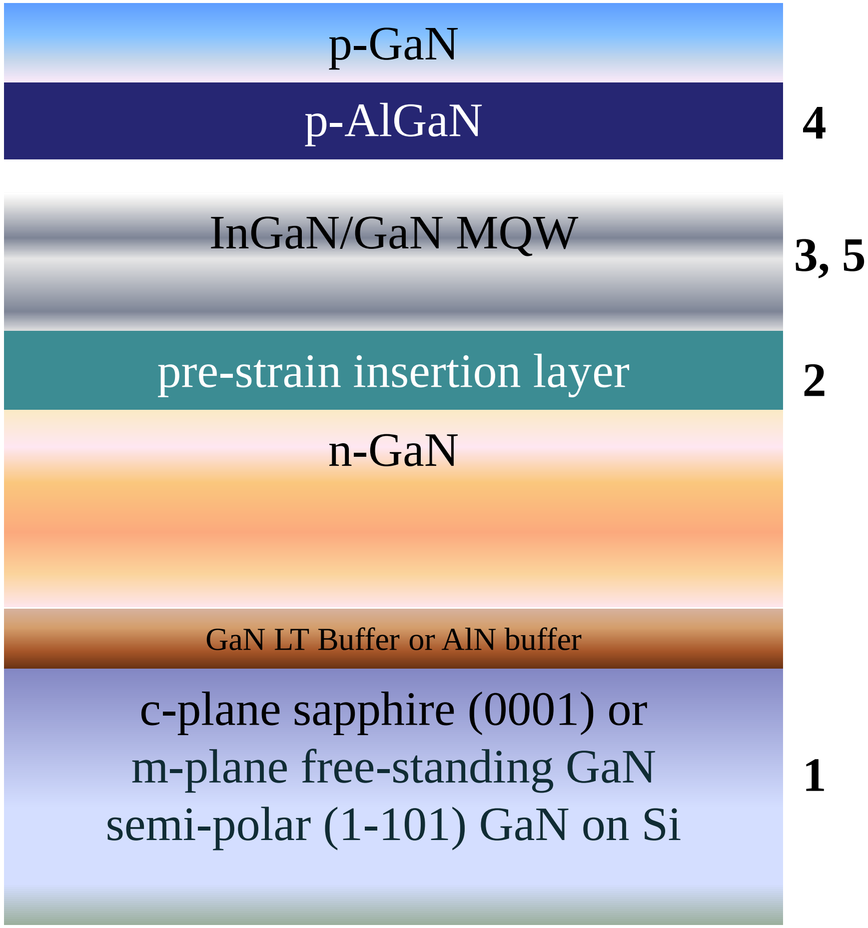
- **EBL design**
  - **graded-composition EBL (GEBL)**

  for hole injection

  Semiconductor Today, SPIE newsroom
  Applied Physics Letters, 2010, 98, 261103

- **Quaternary barrier**
  - **InAlGaN quaternary barriers**

  Compound Semiconductor, *Applied Physics Letters*, 2011, 98, 211107



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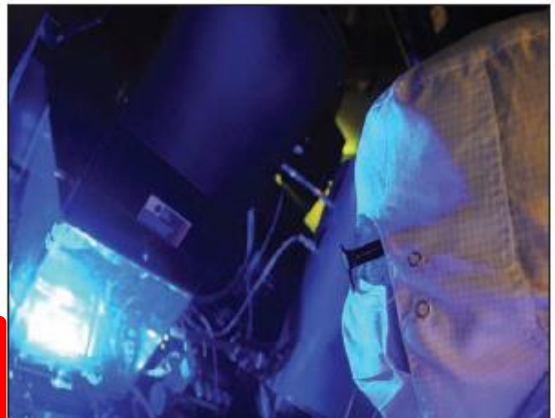
Centre stage
LEDs for general illumination is hot topic at euroLED

Powerful vertical LEDs
Choosing the right wafer-to-wafer bonding process

Full inspection
Comprehensive awareness enables high yield LEDs

Droop drop
Quaternary barrier shows promise



Quaternary barrier cuts droop in UV LEDs

InAlGaN barrier boosts ultra-violet LED output at high current densities

July 2011 www.compoundsemiconductor.net

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SPIE is the international society for optics and photonics

Improving the efficiency of gallium nitride-based LEDs for high-power applications

Chao-Hsun Wang, Chien-Chung Lin and Hao-Chung Kuo

A novel LED structure improves carrier transport behavior and efficiency at high current densities.

semiconductorTODAY

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News

13 January 2011

Good grades for reducing nitride LED efficiency droop

Researchers in Taiwan from National Chiao-Tung University and
graded electron-blocking layer (GEBL) for nitride semiconductor li
reduces efficiency droop compared with devices with a conventior
Phys. Lett., vol97, p261103, 2010]

96 Technology focus: Nitride LEDs

Good grades for reducing nitride LED efficiency droop

Taiwan researchers cut LED efficiency droop from 34% to 4% using graded electron-blocking layer.

- **Efficiency Droop in LED reported by Compound Semiconductor、Semiconductor Today及SPIE Newsroom**
- **Invited talk in Photonic West 2011**

  Photonic West and ICMOVPE 2012

2. Hole injection Improvement by Graded-composition EBL (GEBL)

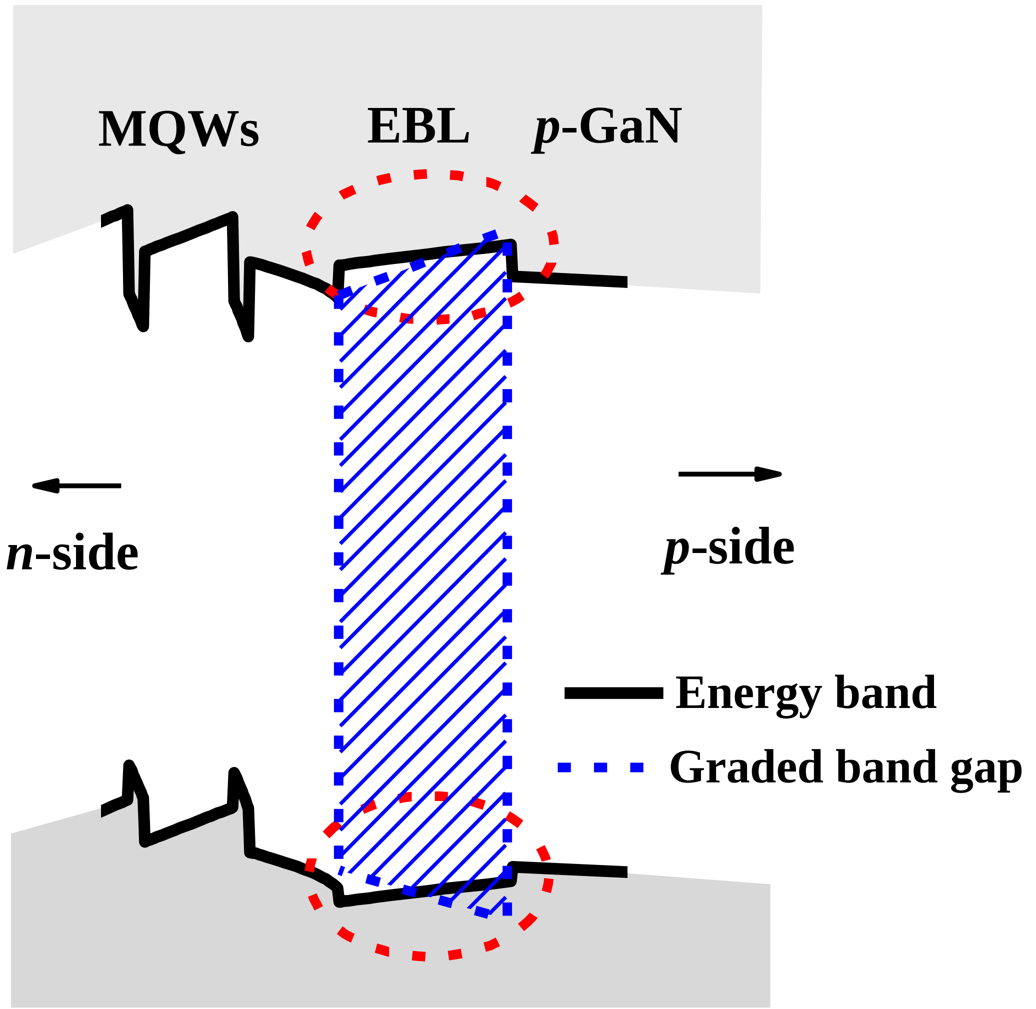
• In conventional LED (black line), the valance band of EBL slopes upward from the *n*-GaN side toward *p*-GaN side.

➢**Retarding the holes to transport across the triangular barrier.**

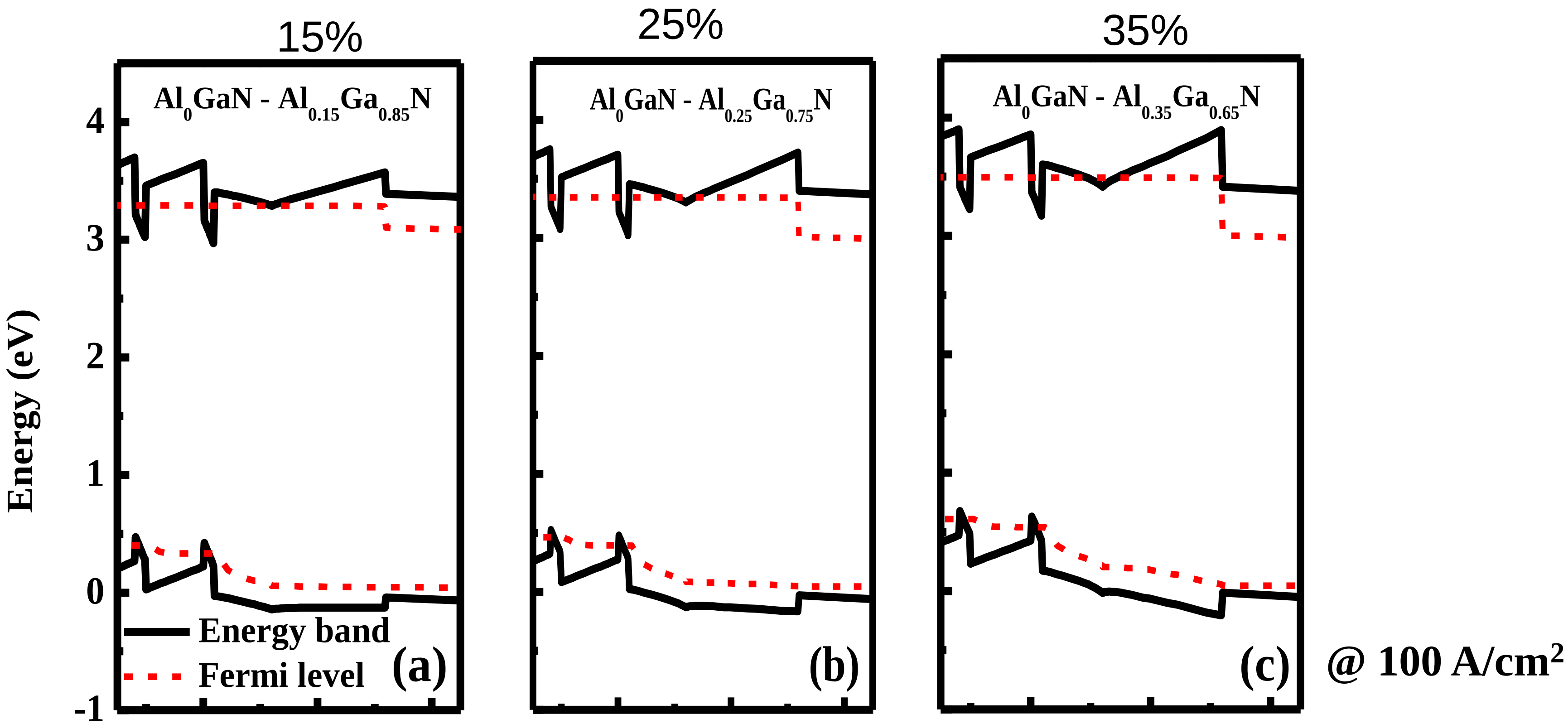
• If the composition of Al in EBL increases from the *n*-GaN side toward *p*-GaN side, the band-gap broadens gradually.

➢ **The barrier in valance band could be level down and even overturn.**

➢**The slope of conduction band could be enhanced.**

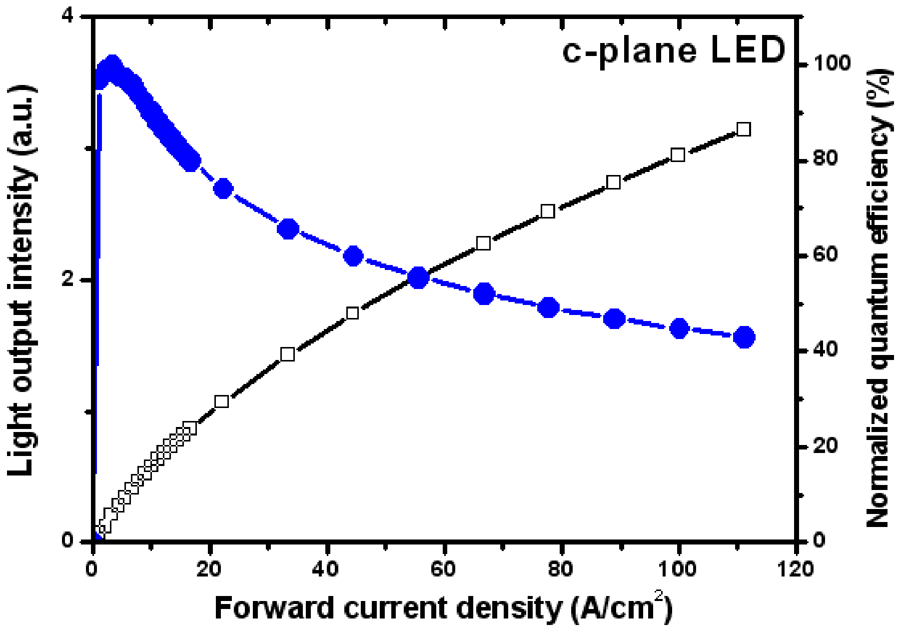


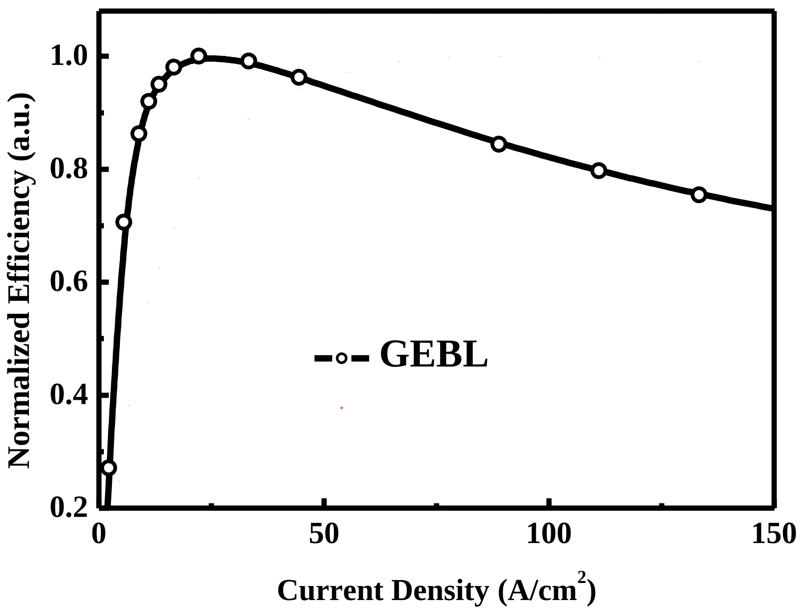
Different composition for GEBL (Simulation with Crosslight)



- ➢ $\triangle E_v$ between the last GaN barrier and the EBL is diminished in all three LEDs with GEBL.
- ➢ Better **electron confinement** and **hole injection** could be expected using GEBL

Characteristics of LED with GEBL





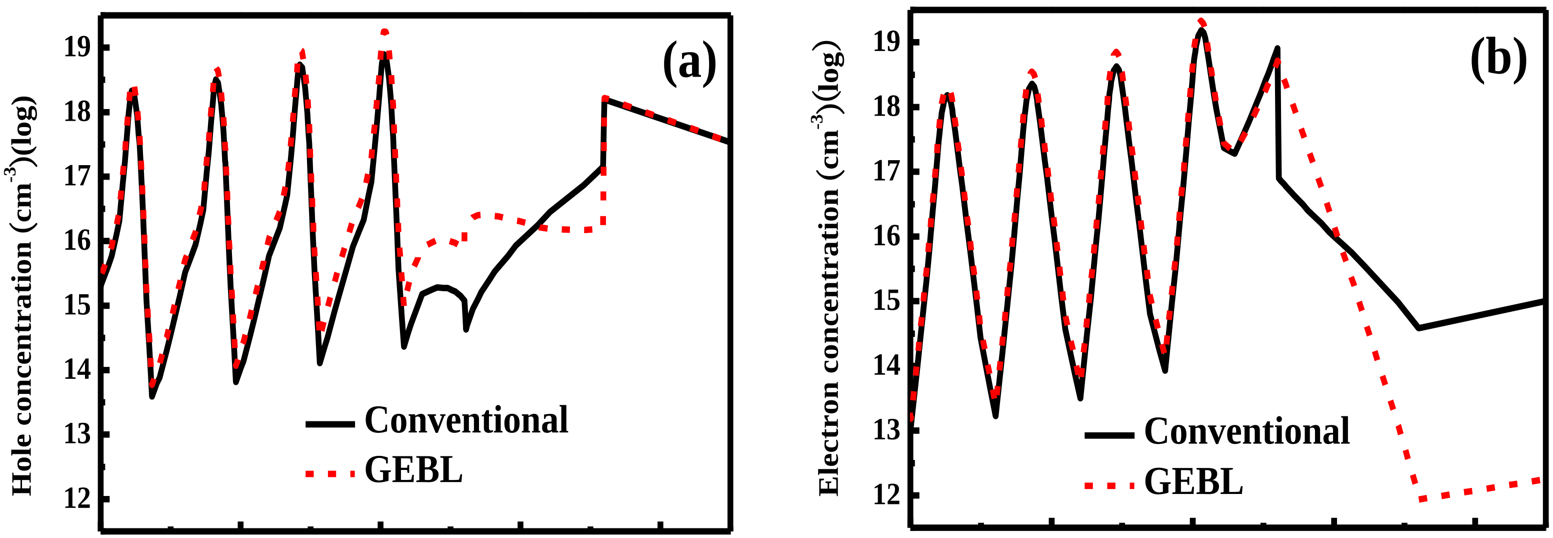
C-plane GaN LED

- Peak efficiency occurs at ~5 A/cm^2
- At 100 A/cm^2
  => Efficiency droop ~ 45%

C-plane GaN with GEBL LED

- Peak efficiency occurs at ~17 A/cm^2
- At 100 A/cm^2
  => Efficiency droop ~23%

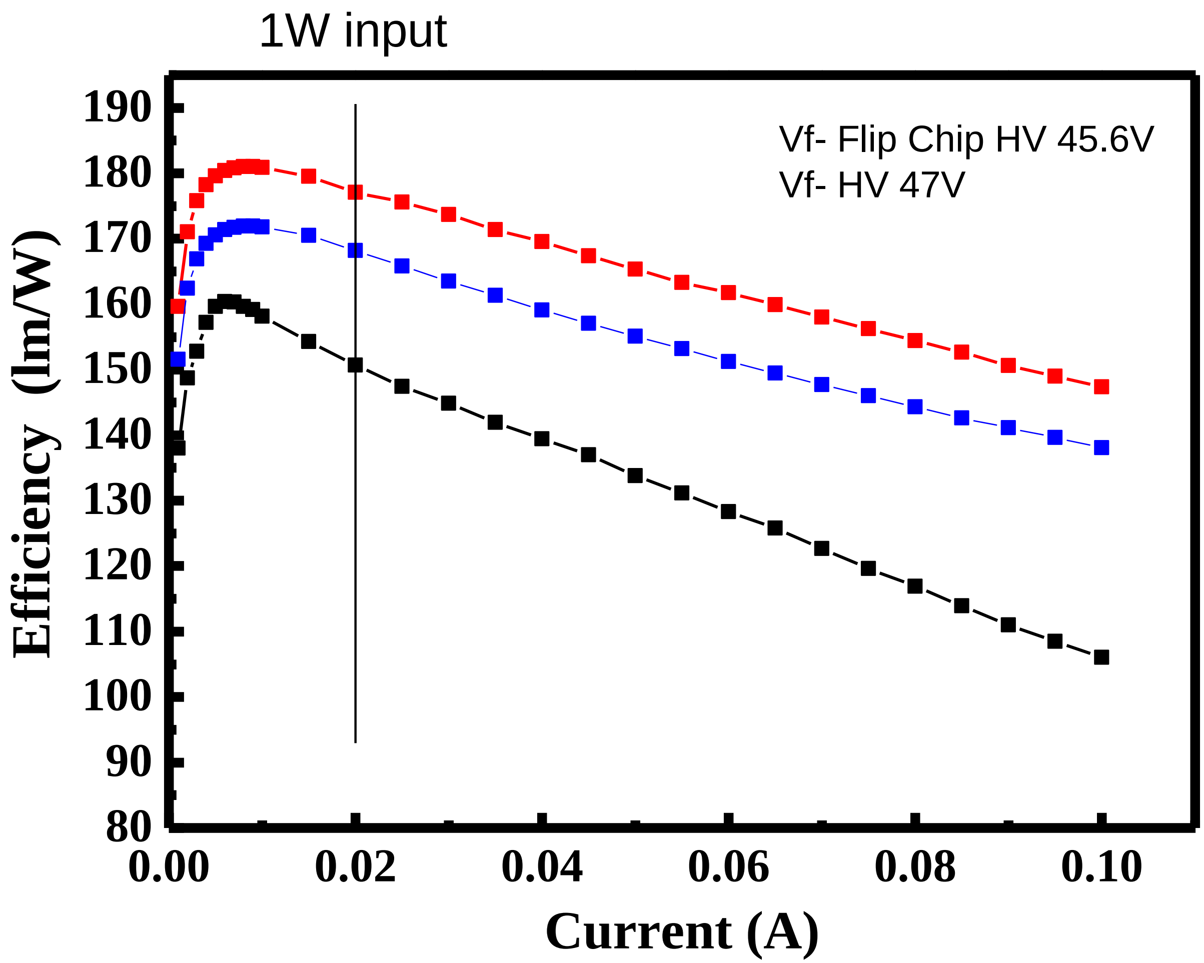
Carrier Distribution LED with GEBL (Simulation)



- Injected holes uniformly distribute along the EBL region compared to conventional LED, and hole concentration in MQWs is significantly increased as expected- better hole transport.

- Electron overflow is more effectively reduced than conventional EBL

HV Flip Chip LED with Graded SL EBL (Epistar)



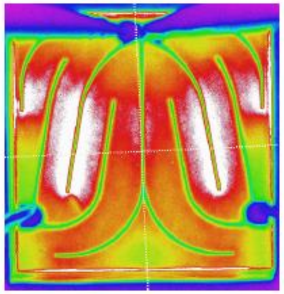
At 0.02A

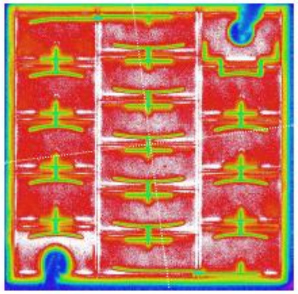
150 lm 150lm/W old structure

157 lm 168 lm/W with SL EBL

162 lm **177 lm/W** with SL EBL

- Ref Face up 45x45 with SL EBL 150 lm/W





CW UV to Blue VCSEL@ RT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Coherent wins PhAST/LFW Innovation Award PAGE 65
LaserFocusWorld
JUNE 2008
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newsbreaks

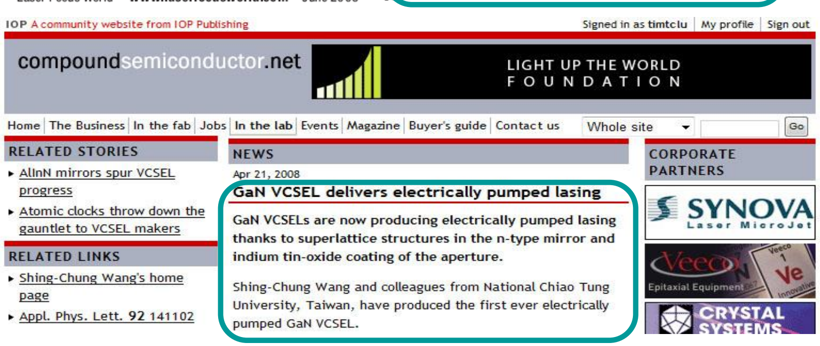
Ultrabright source produces MeV-class gamma rays

Researchers at Lawrence Livermore National Laboratory (Livermore, CA) have announced first light from a novel ultrabright gamma-ray source they call T-REX (Thomson-Radiated Extreme X-rays), intended for isotope-specific, high-resolution detection and imaging applications ranging from science experiments to detection of hidden nuclear materials. The light source

The first electrically injected blue-emitting VCSEL operates at 77 K

Creation of the first directly electrically pumped vertical-cavity surface-emitting laser (VCSEL) has been reported by a group of scientists at National Chiao Tung University (Hsinchu, Taiwan). Operating at the liquid-nitrogen temper-

Laser Focus World www.laserfocusworld.com June 2008 13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RELATED STORIES
- AlInN mirrors spur VCSEL progress
- Atomic clocks throw down the gauntlet to VCSEL makers

RELATED LINKS
- Shing-Chung Wang's home page
- Appl. Phys. Lett. 92 141102

NEWS
Apr 21, 2008

GaN VCSEL delivers electrically pumped lasing

GaN VCSELs are now producing electrically pumped lasing thanks to superlattice structures in the n-type mirror and indium tin-oxide coating of the aperture.

Shing-Chung Wang and colleagues from National Chiao Tung University, Taiwan, have produced the first ever electrically pumped GaN VCSEL.

CORPORATE PARTNERS
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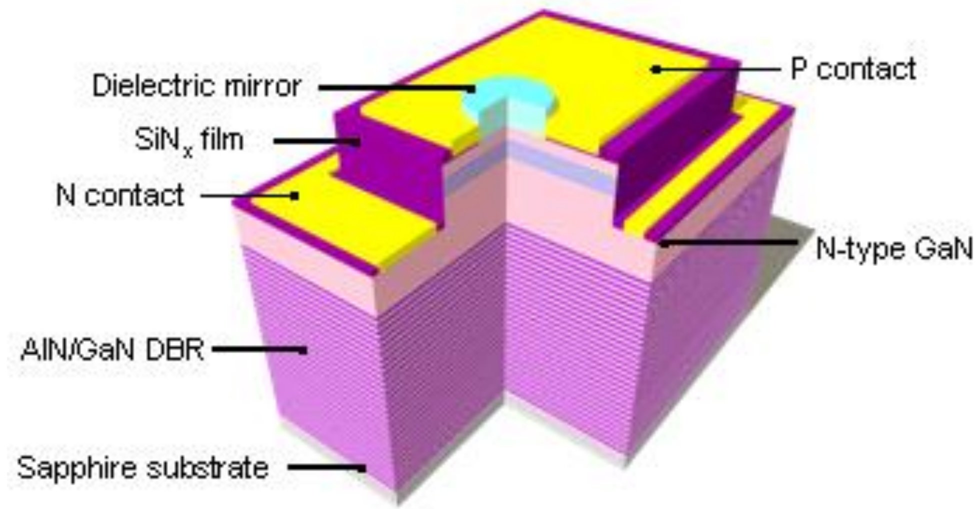
First electrically pump VCSEL Structure -@ RT



AlN/GaN DBR (2004)
Optical pumping GaN VCSEL (2006)
77K Electric pumping GaN VCSEL (2008)
RT Electric pumping GaN VCSEL (2010)

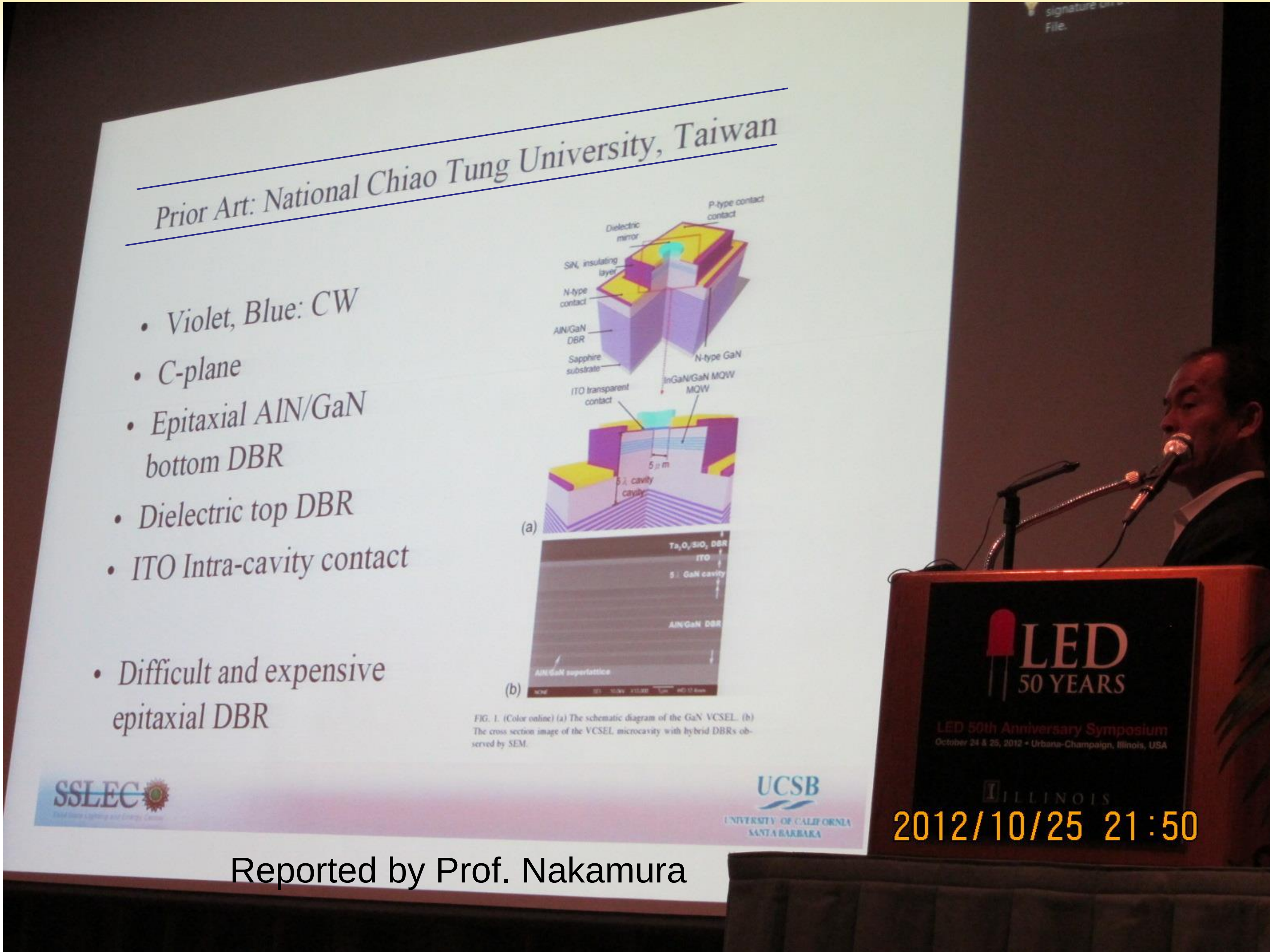
Appl. Phys. Lett. V92, 141102(2008)

CLEO post deadline (2010)

Appl. Phys. Lett. 97, 071114 (2010)

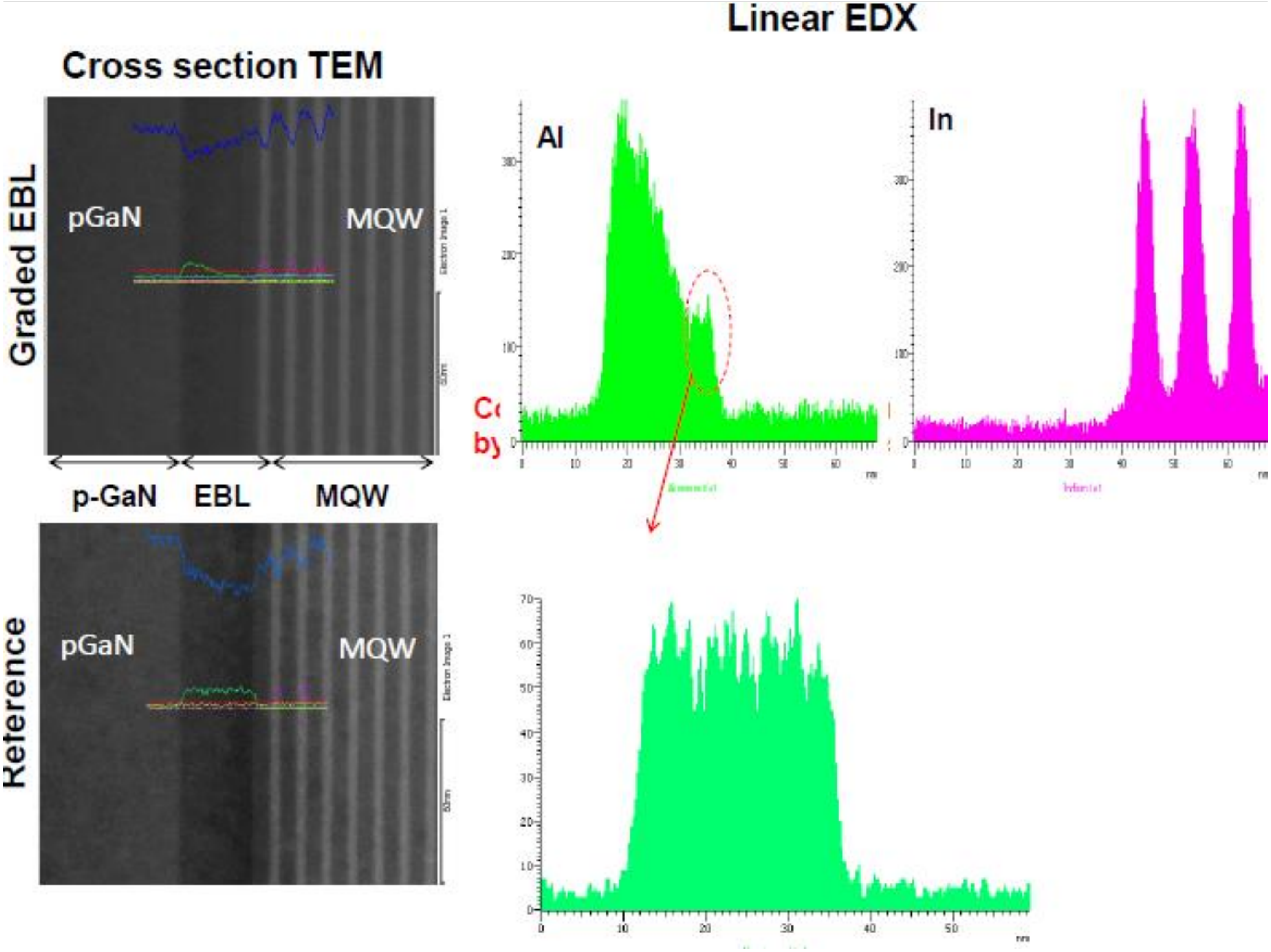
IEEE JSTQE invited paper

AlGaN/GaN DBR - Japan Patent



Reported by Prof. Nakamura

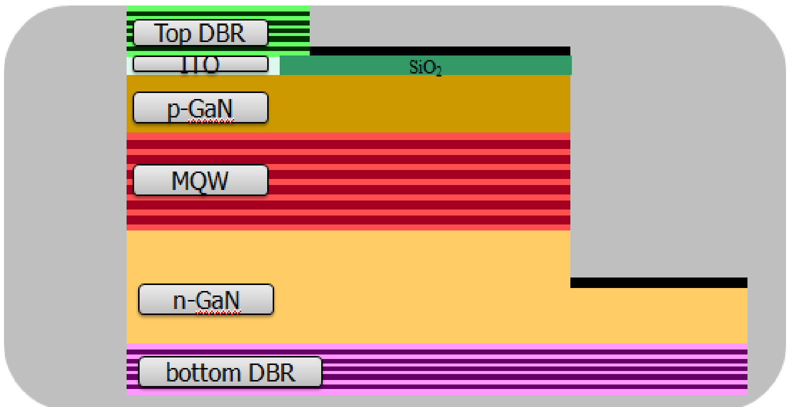
VCSEL with GEBL

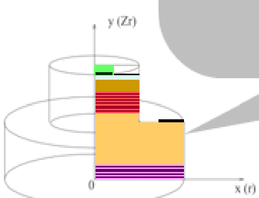


GaN VCSEL with GEBL barrier

Reference structure fitting

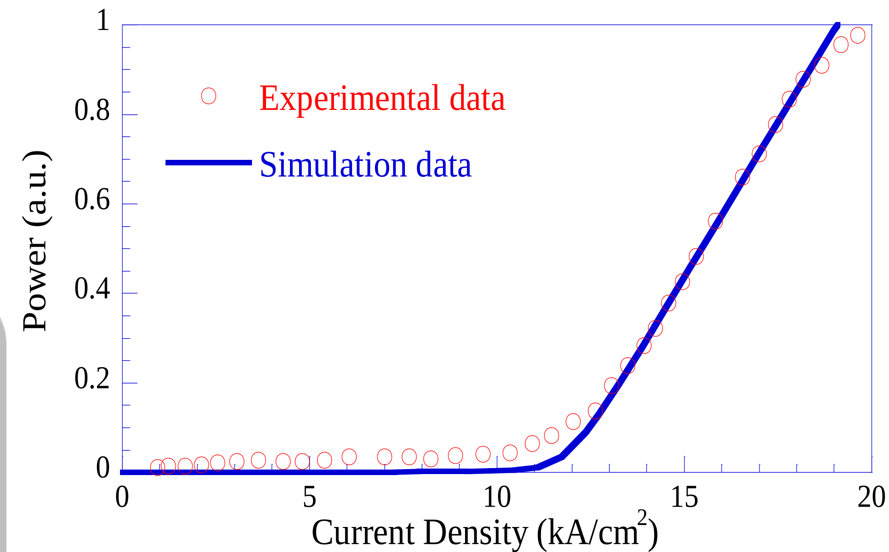
- Simulation structure

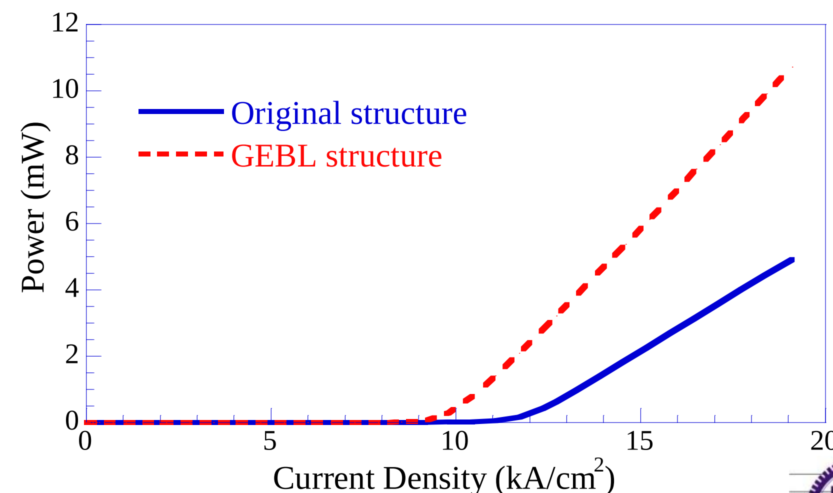




- Version: PICS3D 2010. Macro: Default.
- Current injection apertures: 10 µm (diameter).
- Options: self consistent option.
- [Lu *et al.*, Appl. Phys. Lett. 97, 071114, 2010.]

3

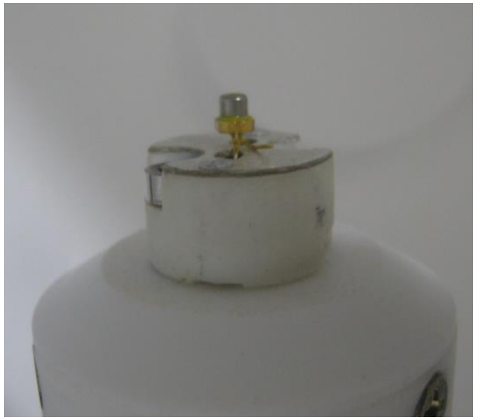


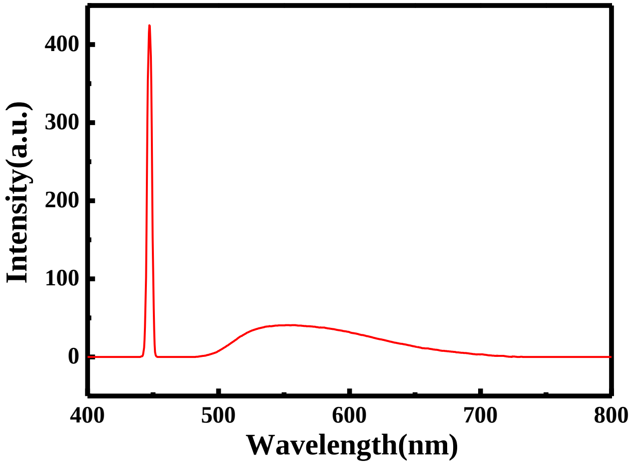


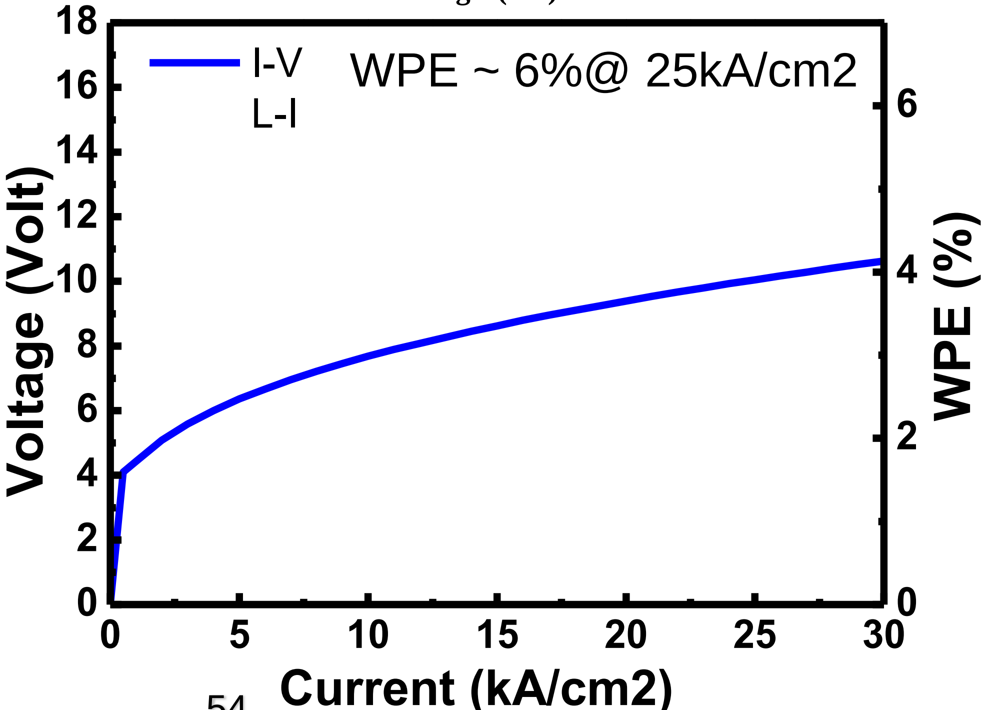
Better Jth (12kA/cm2->9.8kA/cm2) and SE

Laser Physics Letter (2014)

Low Droop due to – low Auger







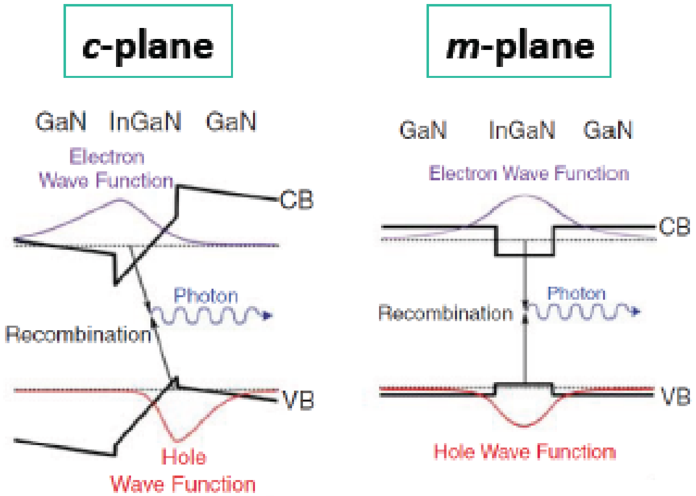
UCSB Experimental data

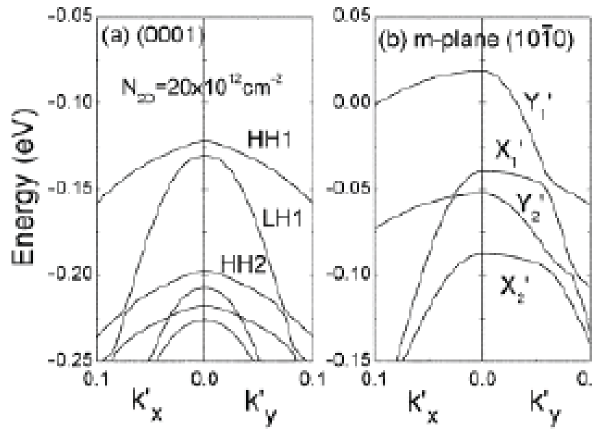
Nearly Droop Free Performance

Outline

- Challenges for Lighting Applications
- LED LEE efficiency (Thin GaN, H-die, flip chip HV)
- Physical mechanisms-efficiency droop
- How to eliminate droop at c-plane LED with strong QCSE
- Graded-composition electron blocking layer (AlGaN)
- Efficiency droop in c-plane and m-plane GaN LED
- Semipolar {10-11} InGaN/GaN Nanopyramid LED

Benefits of Nonpolar/Semipolar





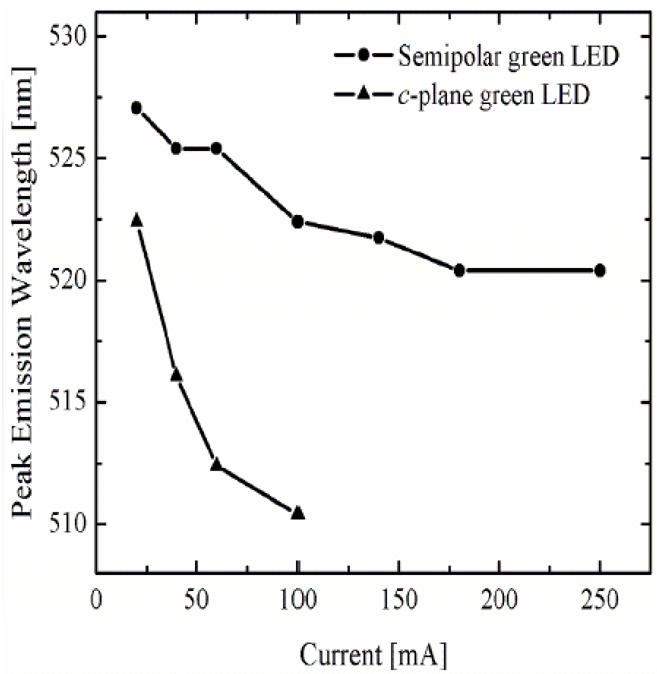
- **Quantum confined stark effect is reduced or eliminated**
- **Optical matrix elements are larger for nonpolar and semipolar orientations**
- **Hole effective mass is smaller for nonpolar and semipolar orientations**
- **Predictions of lower transparency carrier densities and higher differential gains**
- **Reduced blue shift with increasing bias**

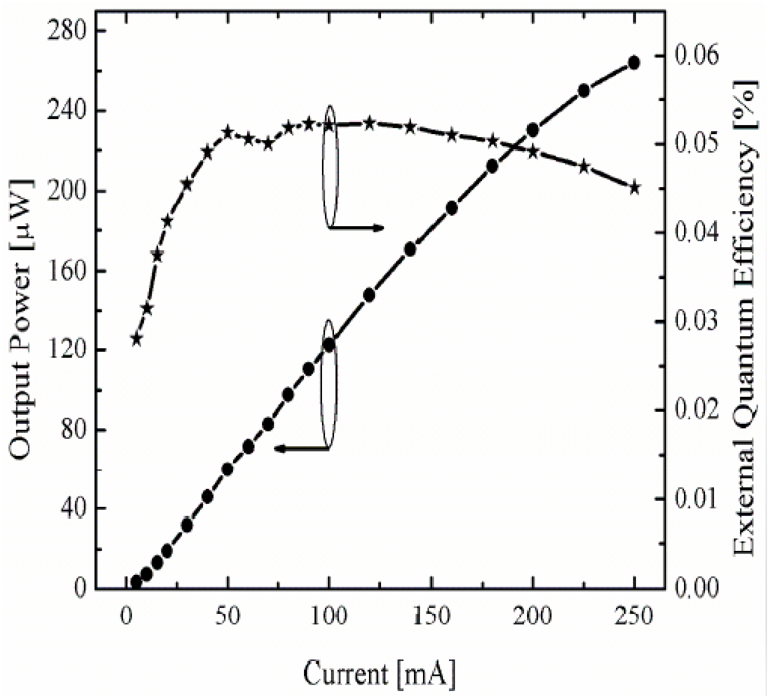
S. H. Park, et al, Jour. Quant. Elec. 43, 1175 (2007).

SSLEC Solid State Lighting and Energy Center

UCSB

Non-polar/Semipolar GaN LEDs (UCSB)

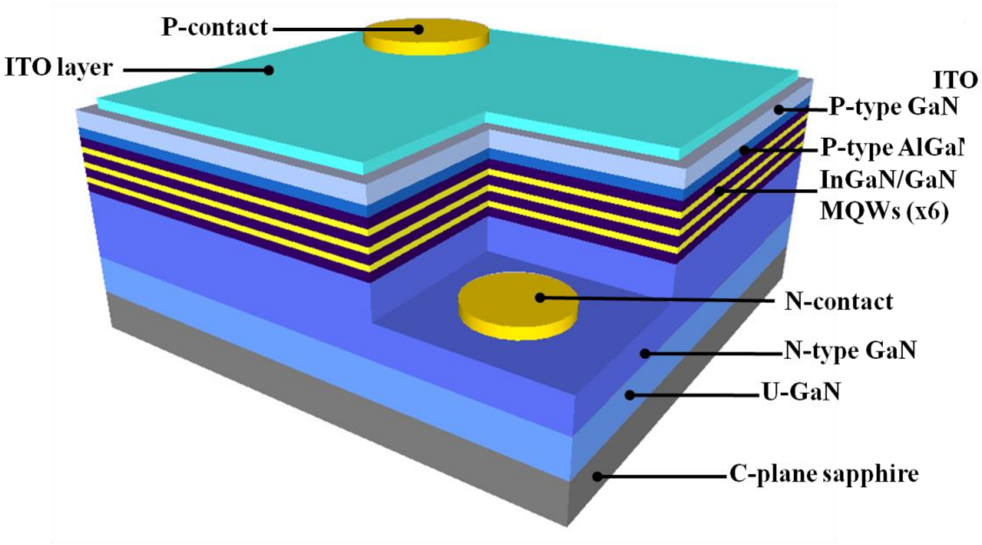


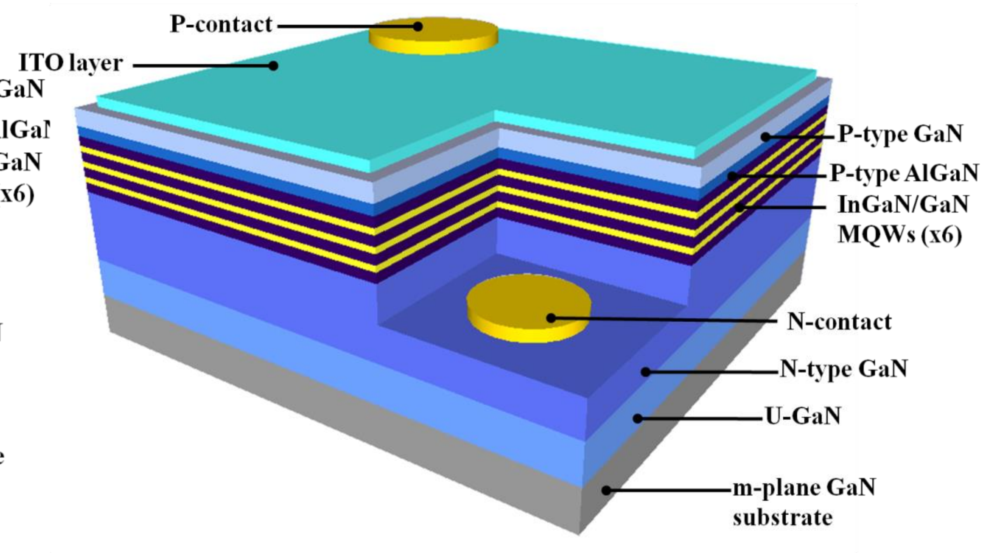


- LED grown on semipolar GaN (10-1-3)
- Reduced polarization fields and QCSE in active region
- Clearly reduces blue shift (direct consequence of polarity reduction)
- "Droop" is still present but improved a lot

Sample Structure

6 pair InGaN/GaN 3nm/12nm

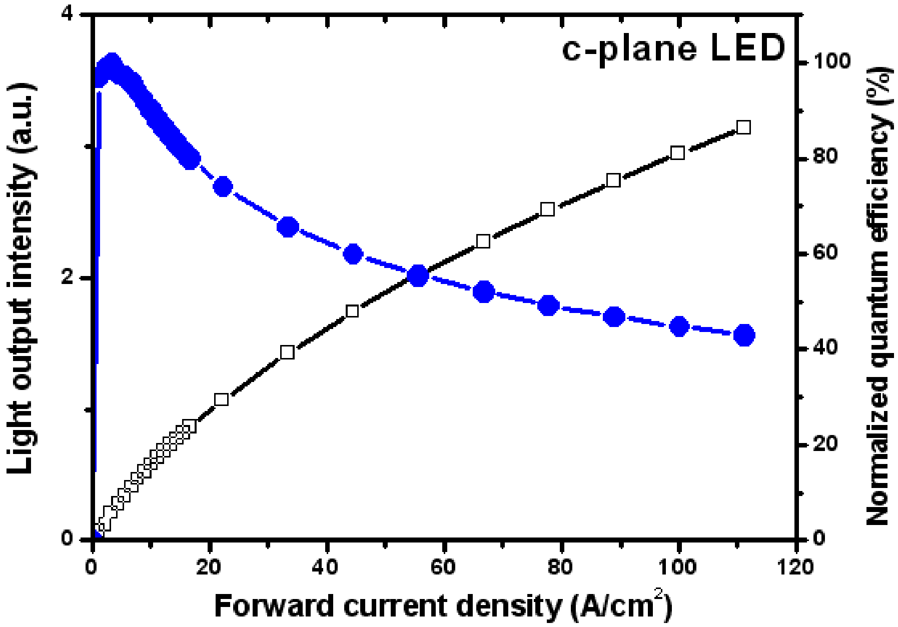


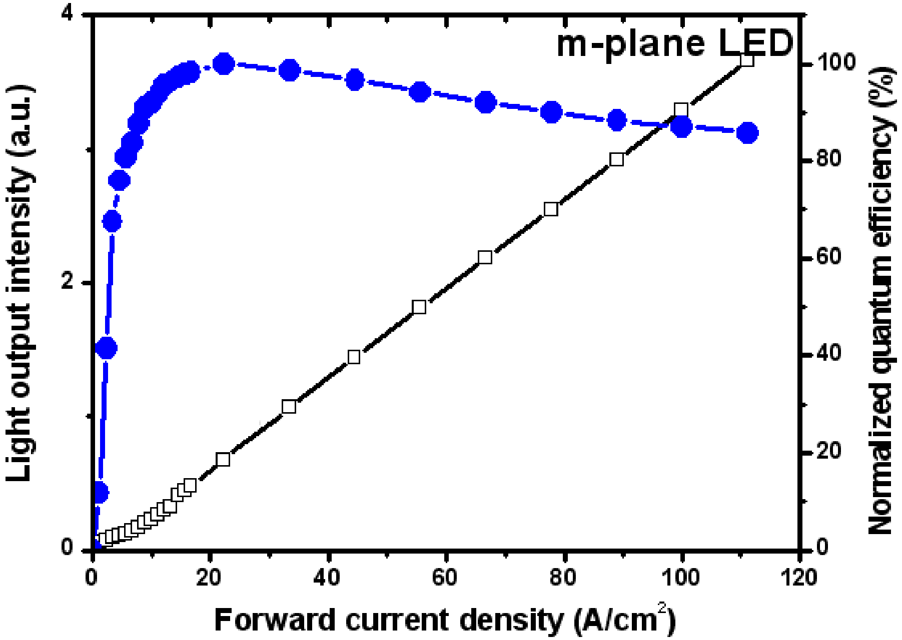


SC Ling and HC Kuo
Applied Physics Letters, 2010, 96, 231101

Kyma

Current-Output Power-Efficiency (460nm)





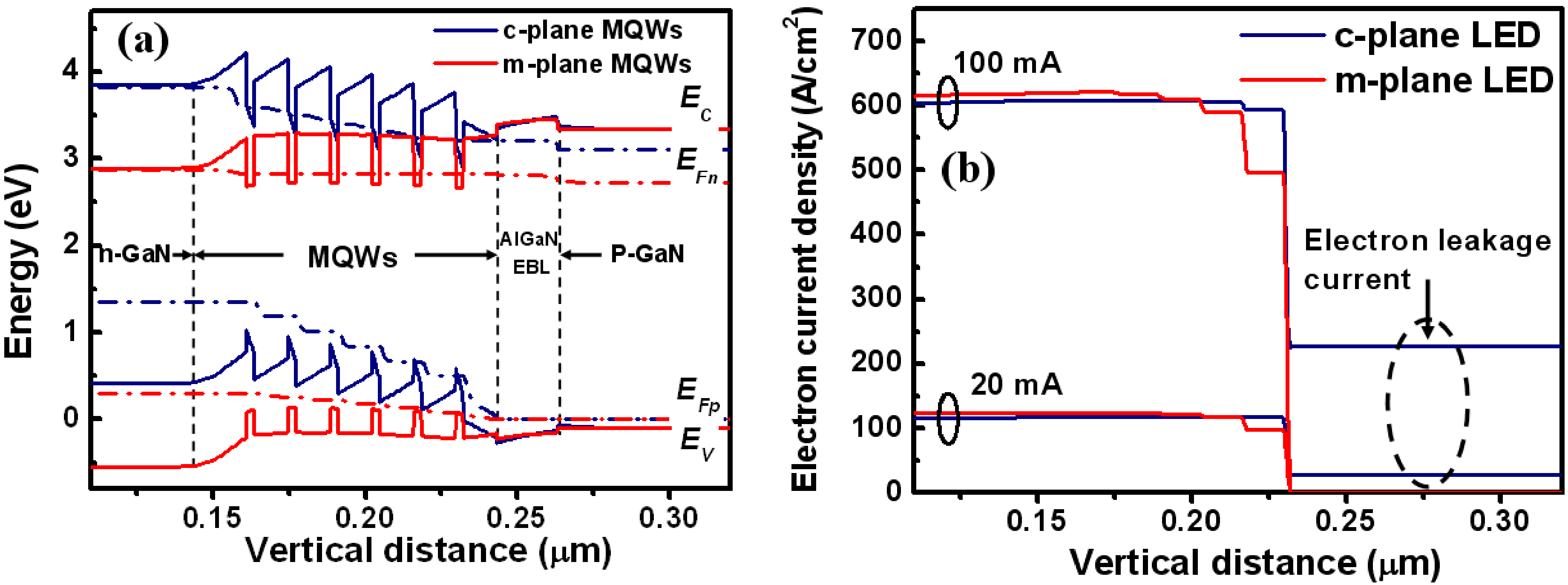
C-plane GaN LED

- Peak efficiency occurs at ~5 A/cm^2
- At 100 A/cm^2
  => Efficiency droop ~ 45%

M-plane GaN LED

- Peak efficiency occurs at ~23 A/cm^2
- At 100 A/cm^2
  => Efficiency droop ~13%

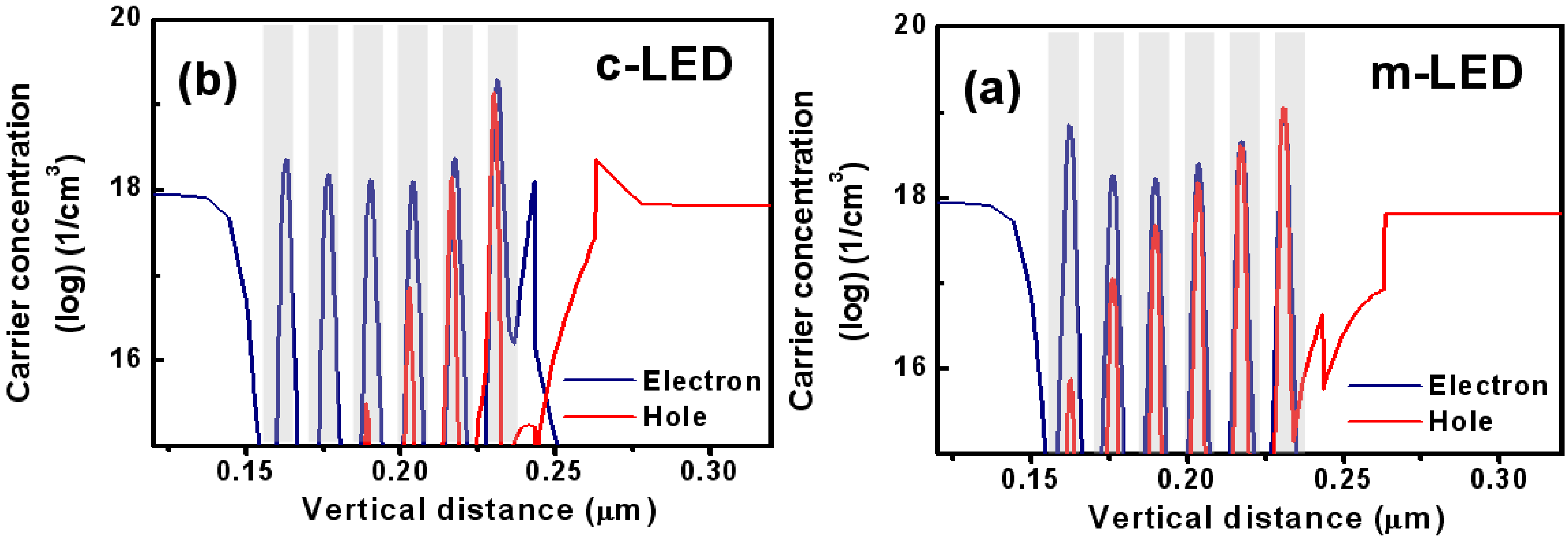
Band Diagram and Current Overflow



• QCSE and band-bending are induced by polarization field in C-plane InGaN/GaN and create triangular energy barrier in active region, which favors electron overflow.

• Polarization field is eliminated by using m-plane GaN, and electron overflow is significantly reduced.

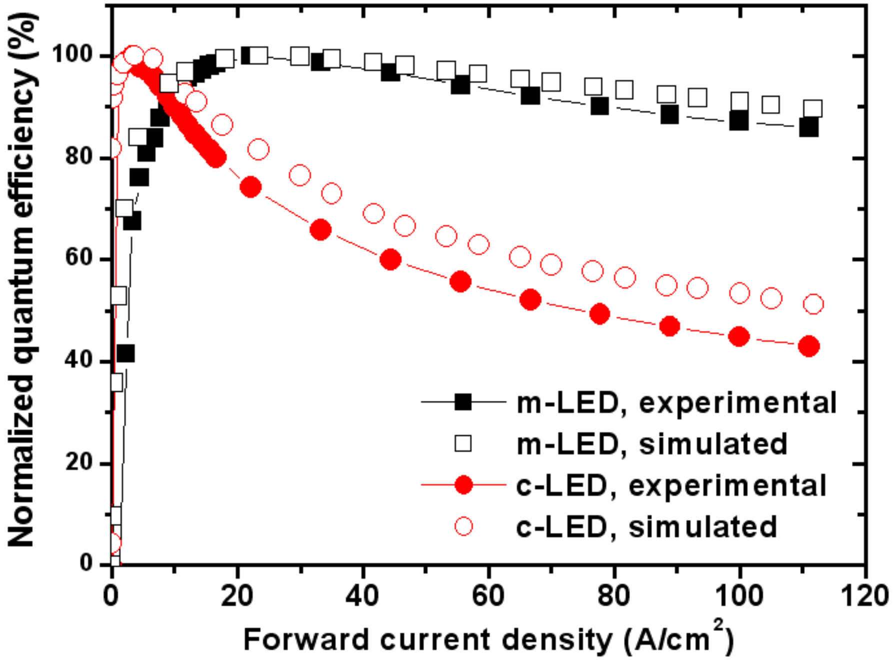
Electron and Hole Distributions



- **Polarization field induces non-uniform hole distribution within MQWs.**
- **Electrons accumulate at the interface between last GaN barrier and AlGaN EBL.**
- **Polarization-free GaN LED has relatively uniform hole distribution due to the elimination of triangular barrier in band diagram.**

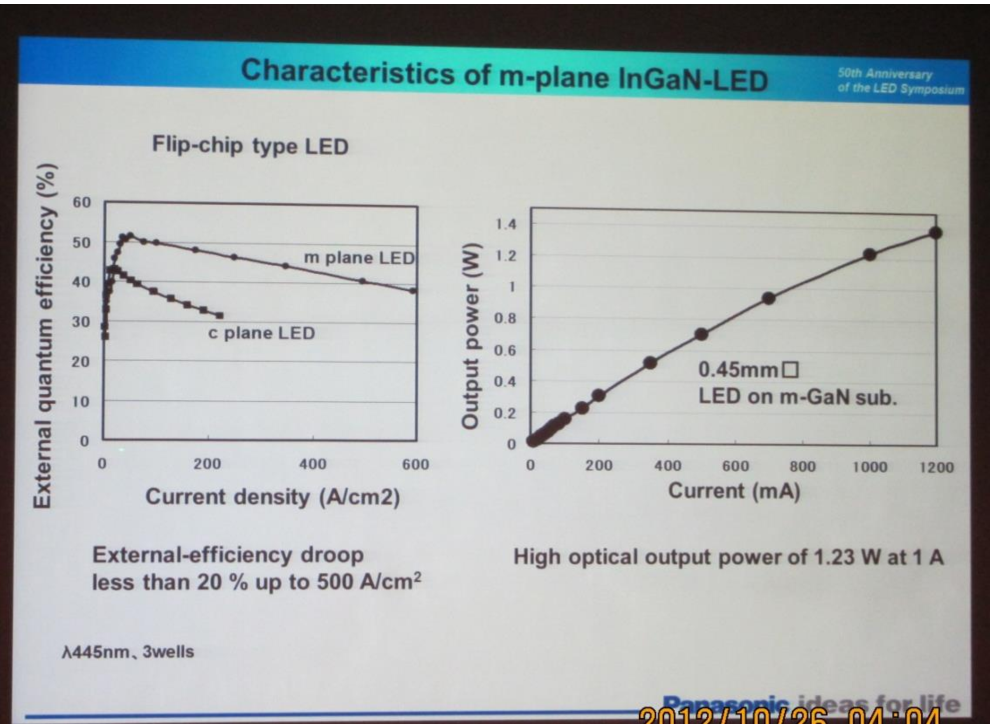
Semiconductor Laser Tech. Lab.

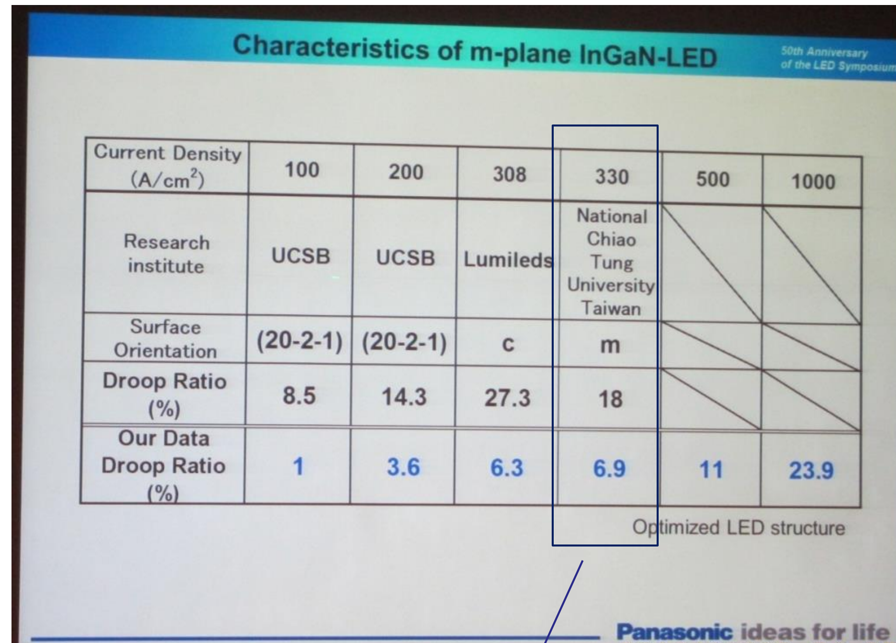
Experimental and Simulated Results



- **Simulation results show good agreement with experiments.**
- **Strongly inherent polarization fields are responsible for the significant efficiency droop of c-plane LEDs.**
- **m-plane LED exhibits the efficiency retention at high current injection as a result of the absence of polarization fields.**

M-plane LED by Panasonic





Characteristics of m-plane InGaN-LED

50th Anniversary of the LED Symposium

Current Density (A/cm^2)	100	200	308	330	500	1000
Research institute	UCSB	UCSB	Lumileds	National Chiao Tung University Taiwan		
Surface Orientation	(20-2-1)	(20-2-1)	c	m		
Droop Ratio (%)	8.5	14.3	27.3	18		
Our Data Droop Ratio (%)	1	3.6	6.3	6.9	11	23.9

Optimized LED structure

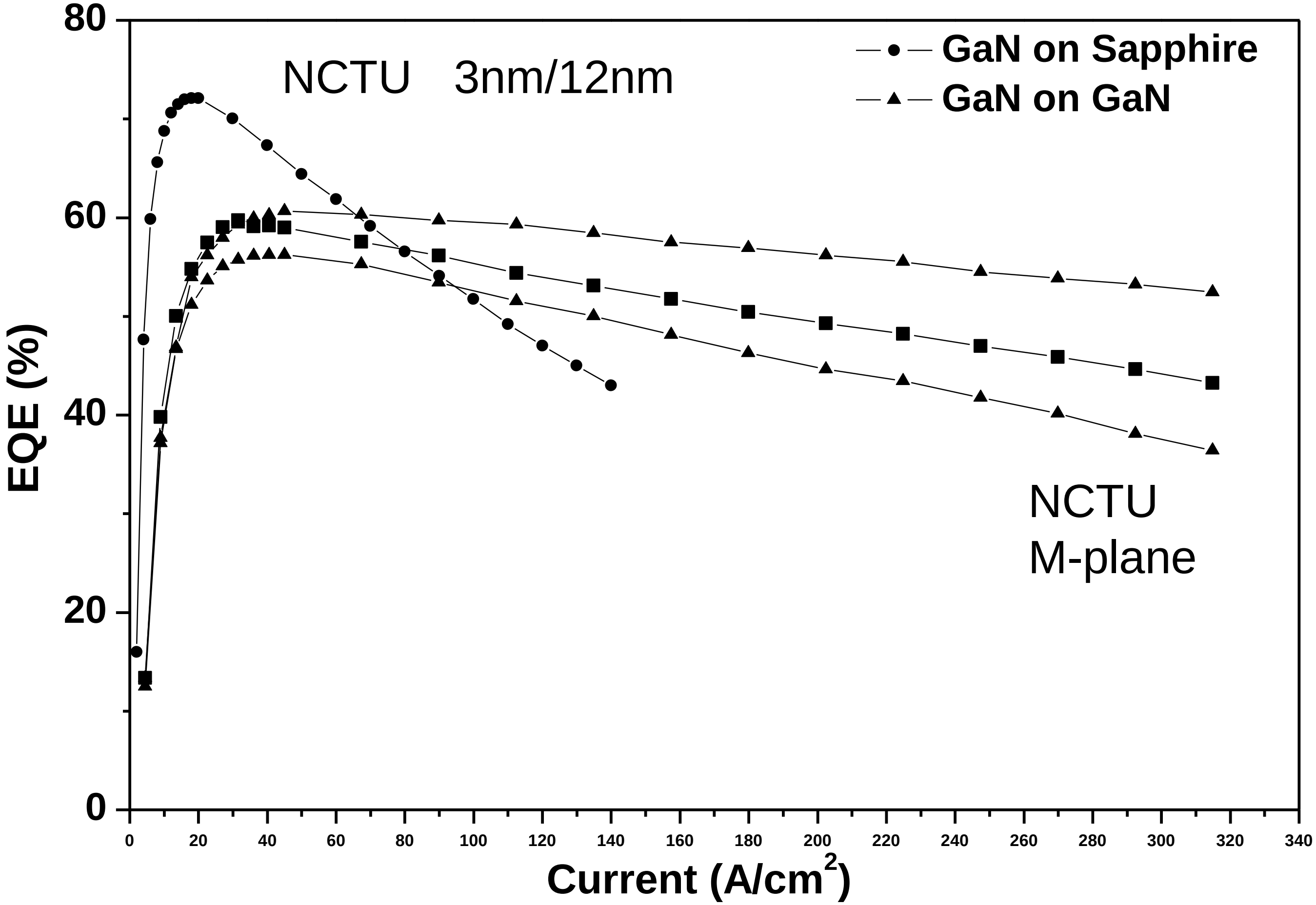
Panasonic ideas for life

SC Ling and HC Kuo
Applied Physics Letters, 2010, 96, 231101

Peak EQE 60% EQE >57% at 200A/cm2 (QW 3nm->6nm/8nm)

M-plane MQWs

NCTU peak EQE 75% (IQE 88%, LEE 85%), 66% 35A/cm2

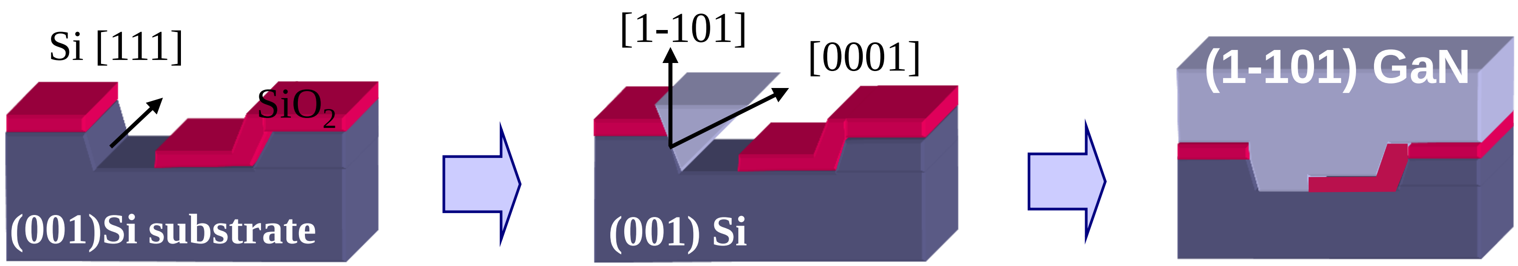


EBL

NCTU data

Chip size 10*23 mil

Semi-polar (1-101) InGaN/GaN multiple quantum wells grown on patterned silicon substrates (with ITRI/Nagoya Univ.)

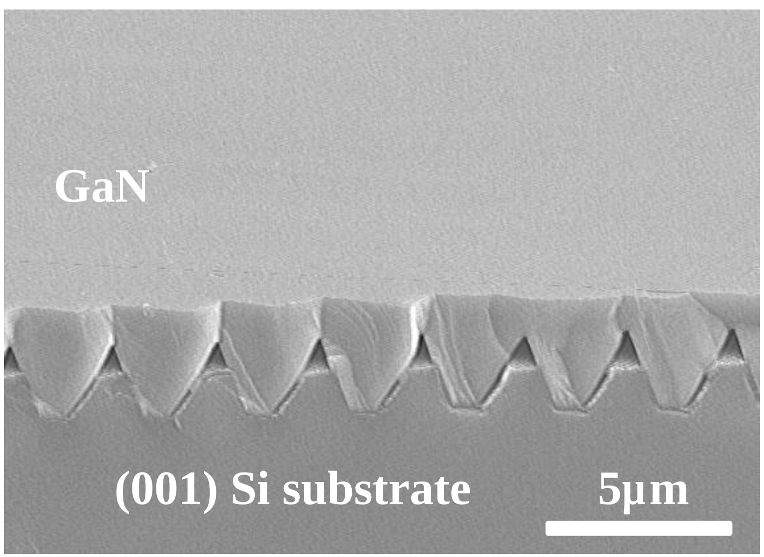


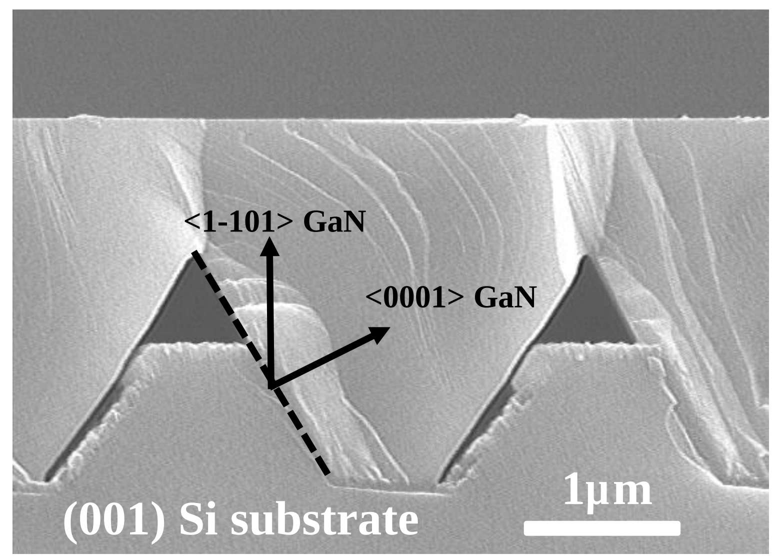
Stripe mask pattern;
Photo-lithography and KOH etching

Selective growth of GaN on (111)Si facets

ELO and Coalescence

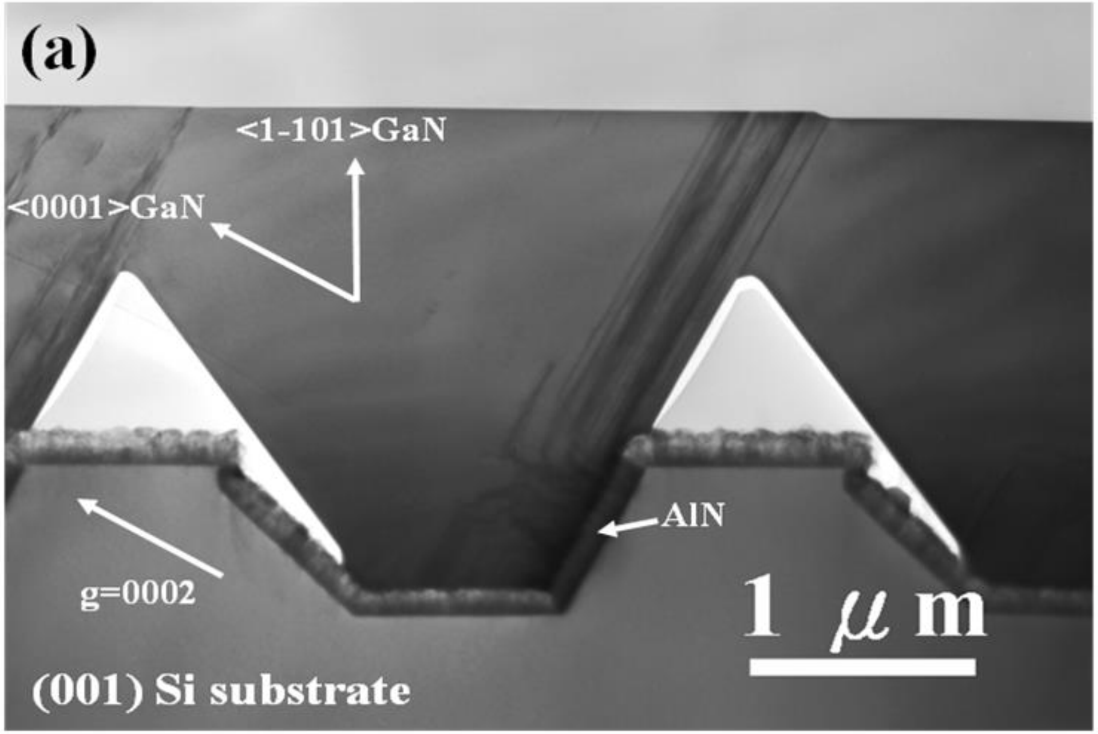
SEM images





◆**High surface quality of the semipolar GaN film**

XTEM Semi-polar (1-101) InGaN/GaN

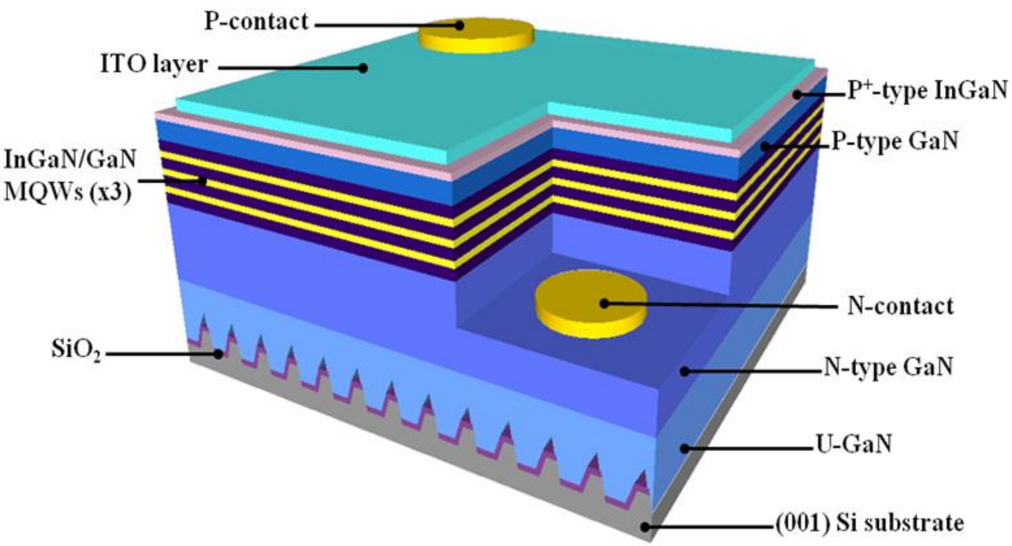


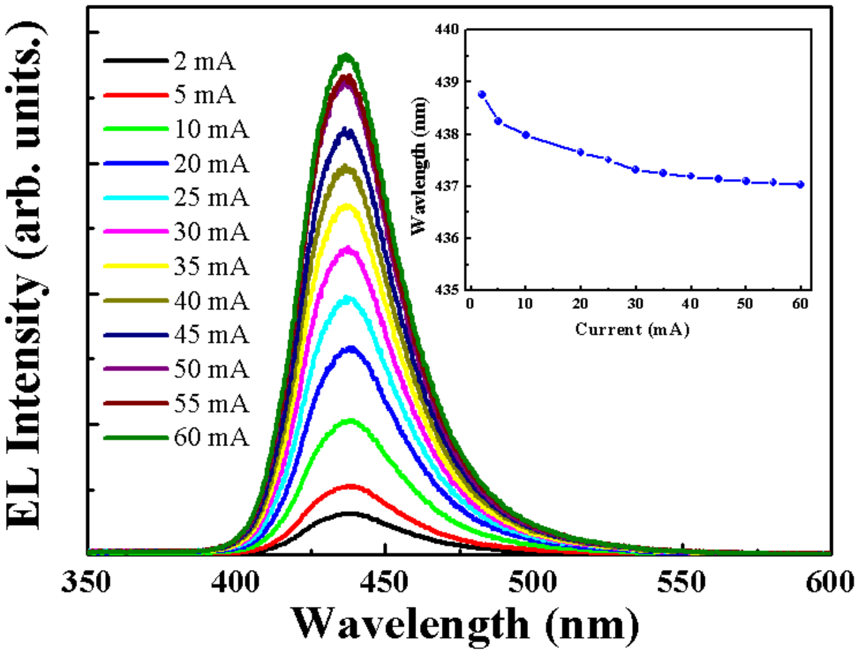
- ◆The threading dislocations generated near AlN buffer layer/Si interface turn to the perpendicular direction of (0001).

- ◆Low TDDs (10E8 1/cm2) at the top of (1-101) as the growth proceeding.

Result-II

3 InGaN/GaN QW 3nm/7.5nm

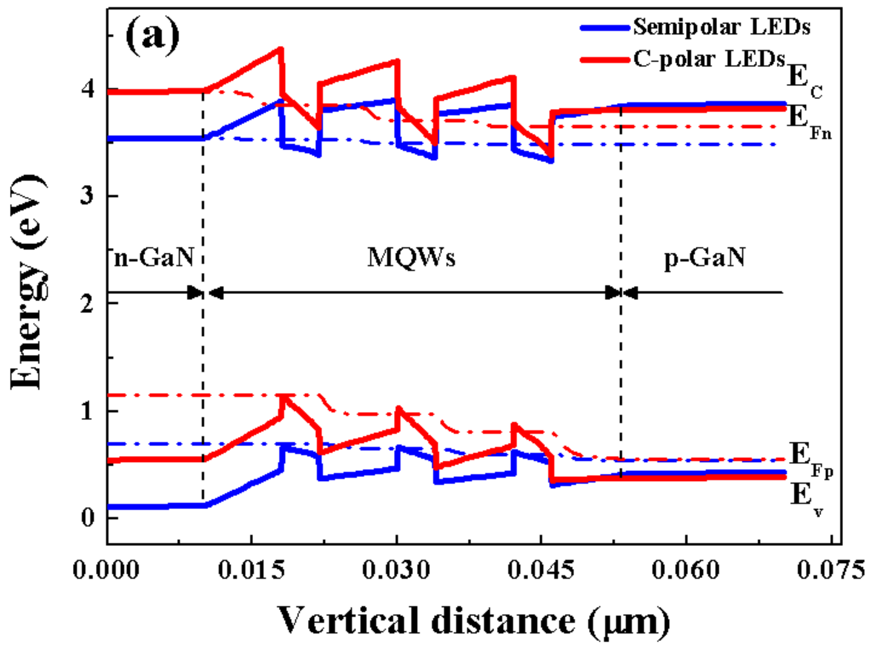


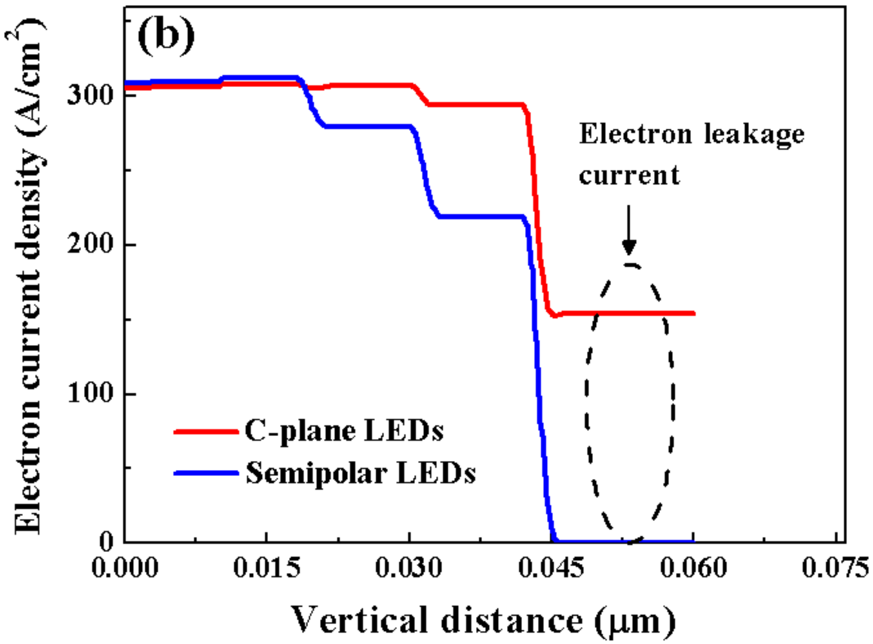


◆**The EL emission peak wavelength of semi-LEDs is slightly blue-shifted (about 1.7nm) at 60mA/cm^2**

◆**EL spectra shows negligible wavelength shift due to less QCSE in semipolar LEDs**

Band Diagram and Current Overflow

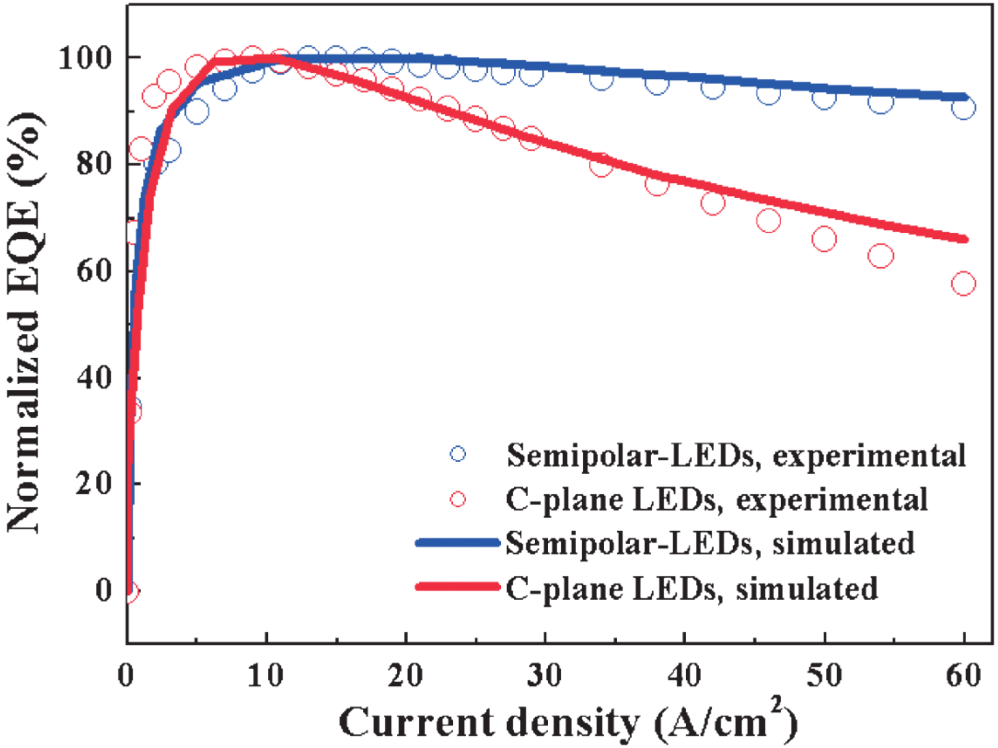




◆Semi-polar GaN reduces polarization field in LED structure.

◆Electron leakage current is significantly reduced in semi-polar GaN based LED.

Simulation result-I



	c-plane	Semi-polar
Screening effect	50%	20%
Auger coefficient (cm^6s^{-1})	$6*10^{-30}$	$7*10^{-30}$
Hole mobility	lower	higher

- Simulation results show good agreement with experiments.
- Internal field dominates the droop behavior in our simulation.
- The efficiency droop improved from 42% to 10%

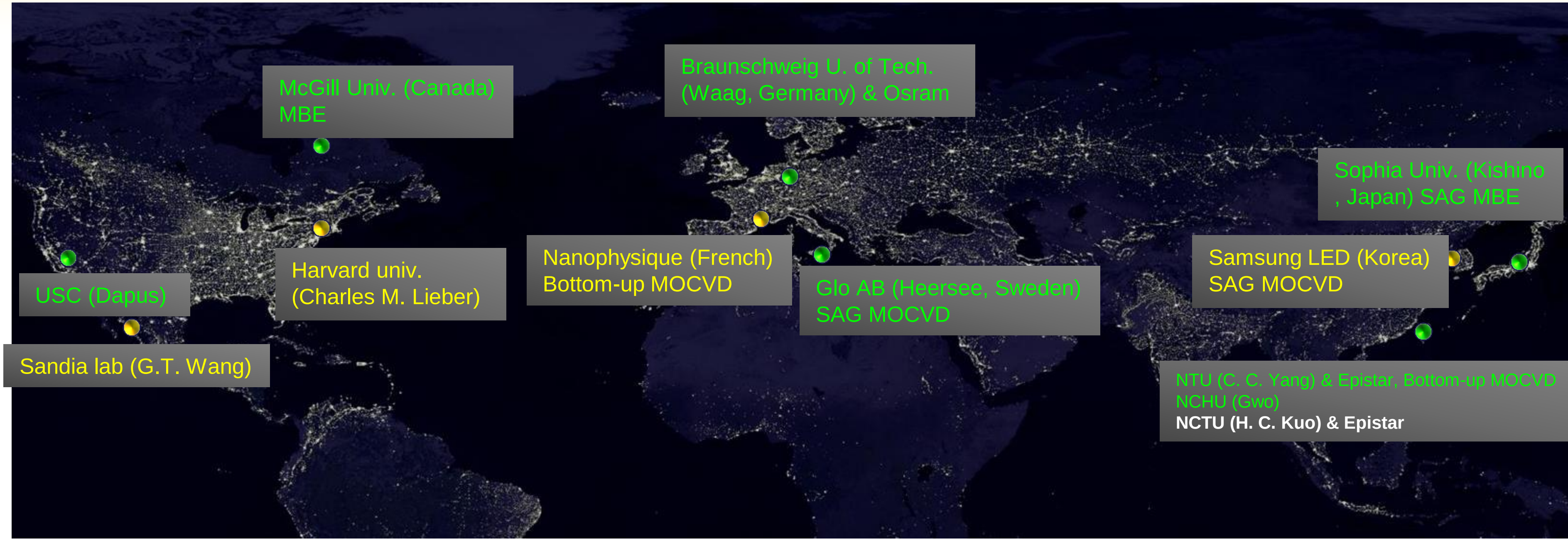
Summary (I)

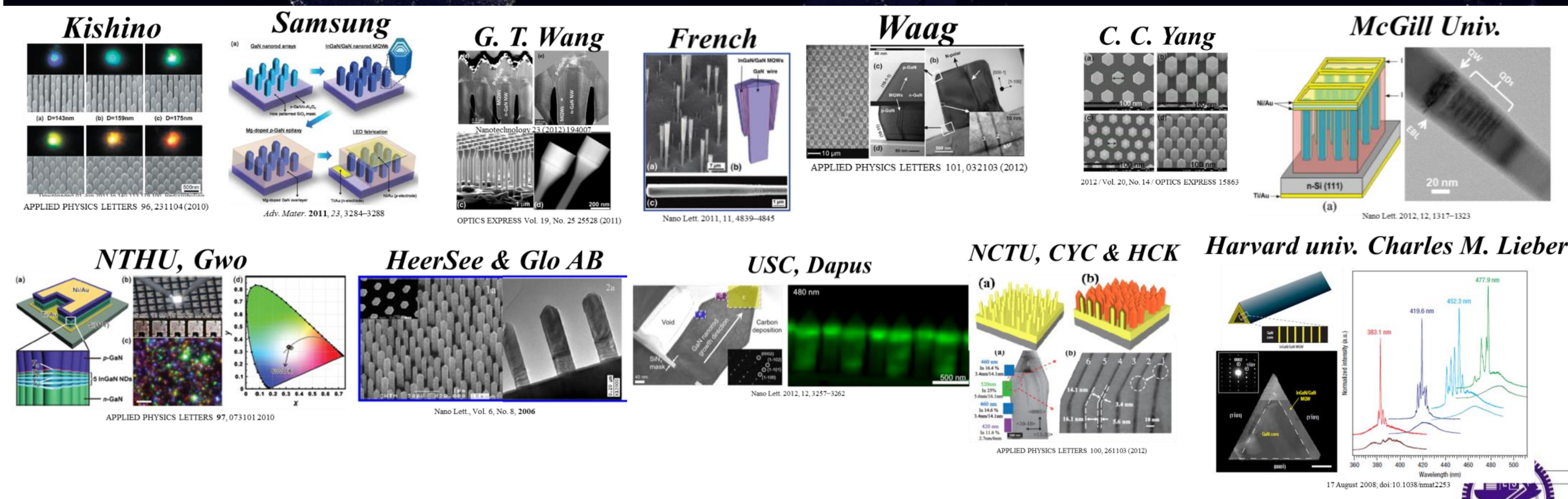
- Several methods for reduction of **efficiency droop** were proposed.
  - *Non-polar and semi-polar GaN substrate to reduce QCSE and overflow*
  - *GEBL structure to enhance hole transportation and reduce electron overflow*
  - *HV LED combine with GBEL design and Red HV LED – 170lm/W 2700K CRI 90 was achieved*
  - *M –plane LED with wider well (6nm, 6 QW) peak EQE 60%, 57% 200A/cm2 only 5% drop (cost)*

NanoLEDs, a new breakthrough for the LED industry

Xavier Hugon and Philippe Gilet of HelioDEL and Patrick Mottier of Leti explain how nanowire-based LEDs can improve LED efficiency and cost reduction for solid-state lighting applications.

Research Activity of GaN nanostructures

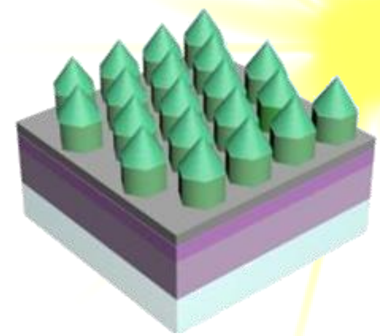




Nanorod LED

How to Improve the Efficiency of LEDs ?

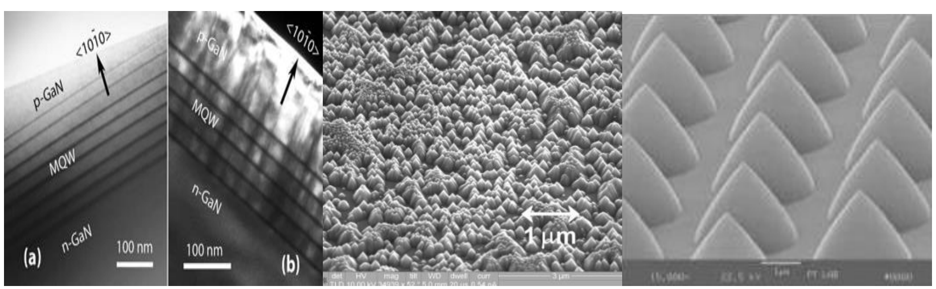
- **Efficiency of LED :** $\eta_{EQE} = \eta_{IQE} \times \eta_{LEE}$ **nanorod LEDs**

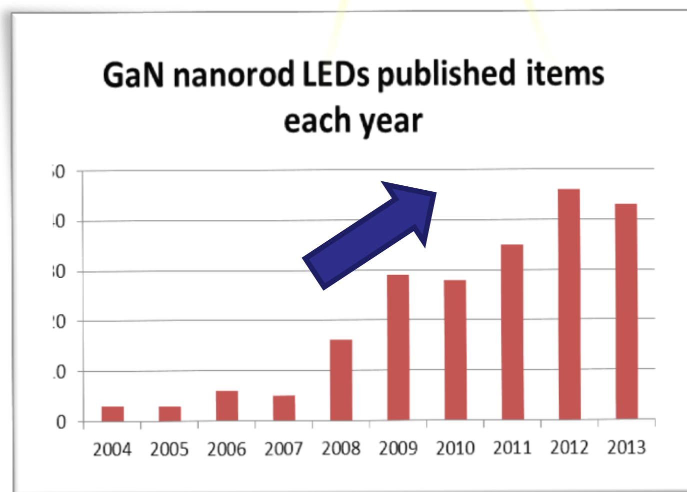


Improving methods:

- ☐ **Internal quantum efficiency (IQE)**
  - Superlattices (SLs)[1]
  - Patterned template [3]

  } **Defect density** ↓
  - Nonpolar / Semipolar substrate[2] **QCSE** ↓
- ☐ **Light extraction efficiency (LEE)**
  - Surface roughness [4]
  - Reflector (DBR, metal etc.) [5]





● **Nitride-based nanorod LEDs attract a lot of attentions in the last few years.**

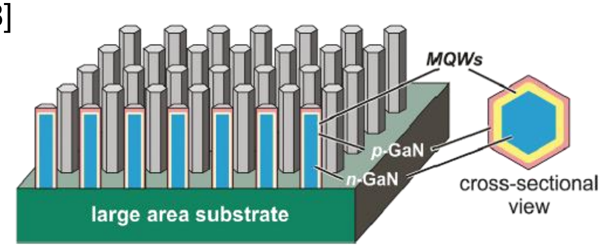
[1] J. P. Zhang et. al., Appl. Phys. Lett. 80, 19 (2002)
[2] Arpan Chakraborty et. al., Appl. Phys. Lett. 85, 22 (2004)
[3] Y. J. Lee et.al., IEEE Photon. Technol. Lett. 18, 1152 (2006)
[4] T. Fujii et. al., Appl. Phys. Lett. 84, 6 (2004)
[5] Jong Kyu Kim et. al., Appl. Phys. Lett. 84, 22 (20040
[6] From Web of Knowledge, retrieved 06/2014

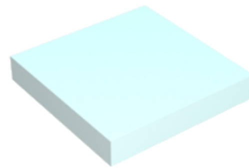
Advantages of Nanorod LEDs

- **Larger area of active layers[7]**

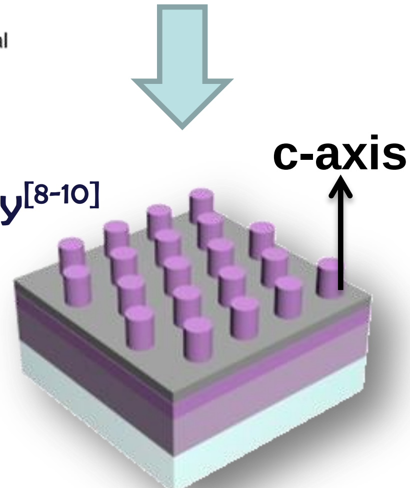
2D → 3D $\frac{A_{rod}}{A_{film}} = \frac{2\pi rh}{\pi r^2} = \frac{2h}{r}$

[8]





2D Template

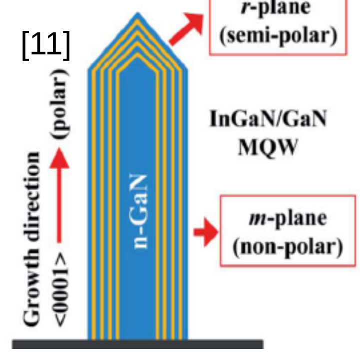


3D nano structure template

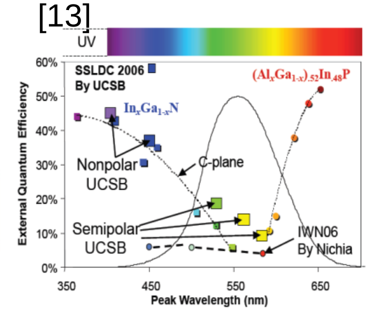
- **Growth of non/semi-polar MQWs[11-13]**

QCSE ↓

[11]

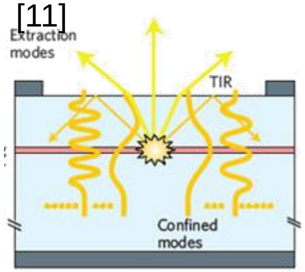


[13]

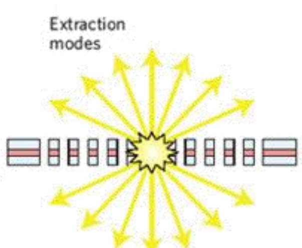


- **Higher light extraction efficiency[8-10]**

Planar LED [11]



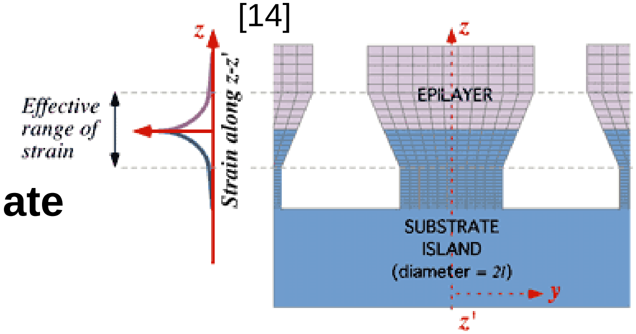
Nanorod LED



- **Strain energy relaxation[14]**

Crystal quality ↑ IQE ↑

[14]

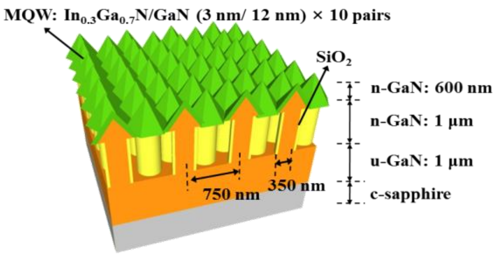


[7] S. Li et al, J. Appl. Phys., 111, 071101 (2012)
[8] H. Y. Ryu, Nanoscale Research Letters, 9:58 (2014)
[9] M. Y. Ke et al, IEEE J. Quantum Electron, 15, 4 (2009)
[10] S. Noda et al, Nature news & views, 3, (2009)
[11] Y. H. Ra et al, J. Mater. Chem. C, 2, 2692–2701 (2014)
[12] S. Nakamura, MRS bulletin, vol. 34, p. 101-107, (2009).
[13] James S. Speck, Solid State Lighting, UCSB
[14] S. D. Hersee et al, J. Appl. Phys. 85, 6492 (1999)

Summary of Nanostructure advantages

•**GaN Nanorods produce zero dislocation, non-polar/semipolar facets on which to grow LED active regions.**

•**The creation of non-polar /semi-polar planes on conventional orientation substrates accesses the advantages of non-polar/semipolar orientations without the cost of bulk substrates.**

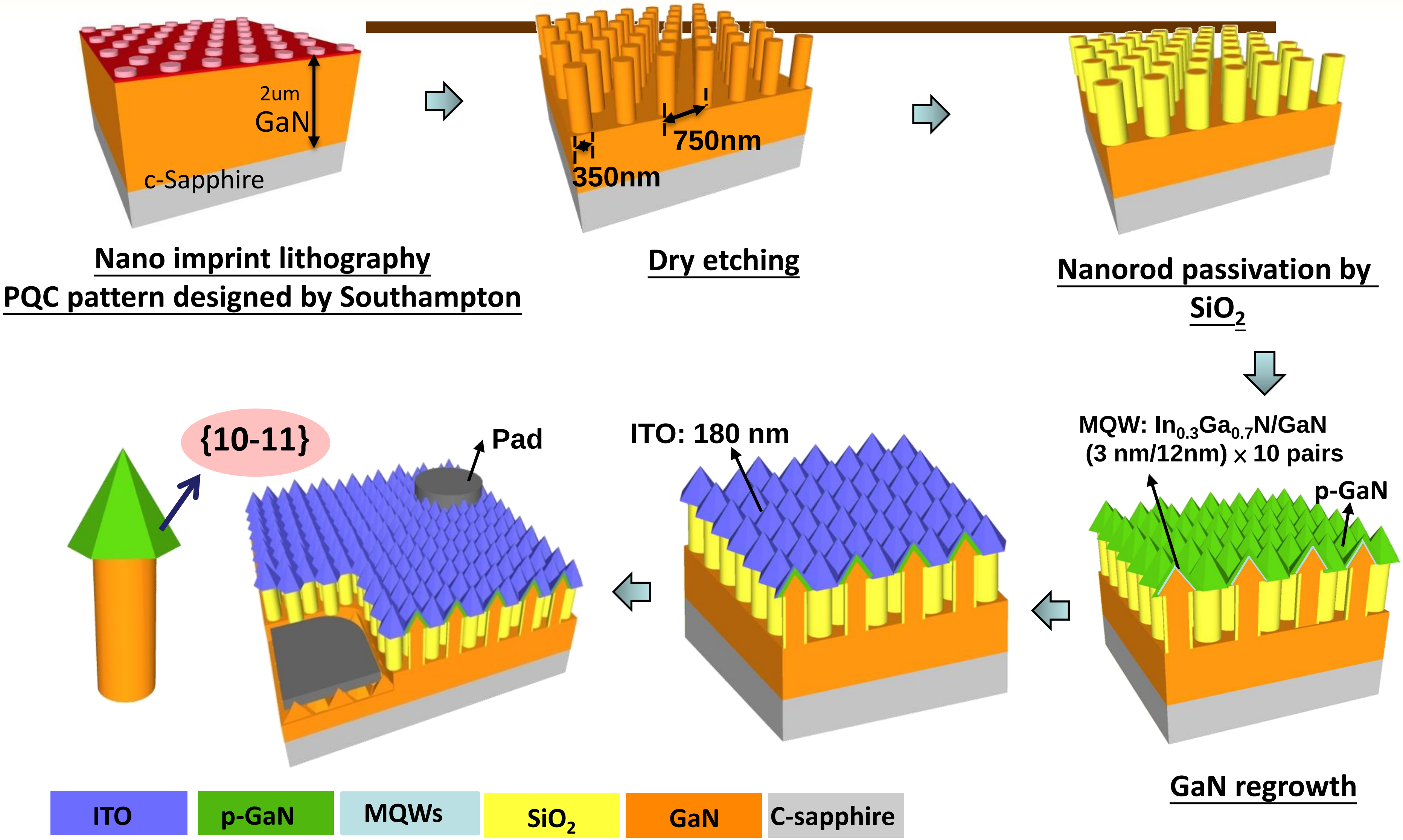


•**3D active regions may further reduce the efficiency droop associated high current operation.**

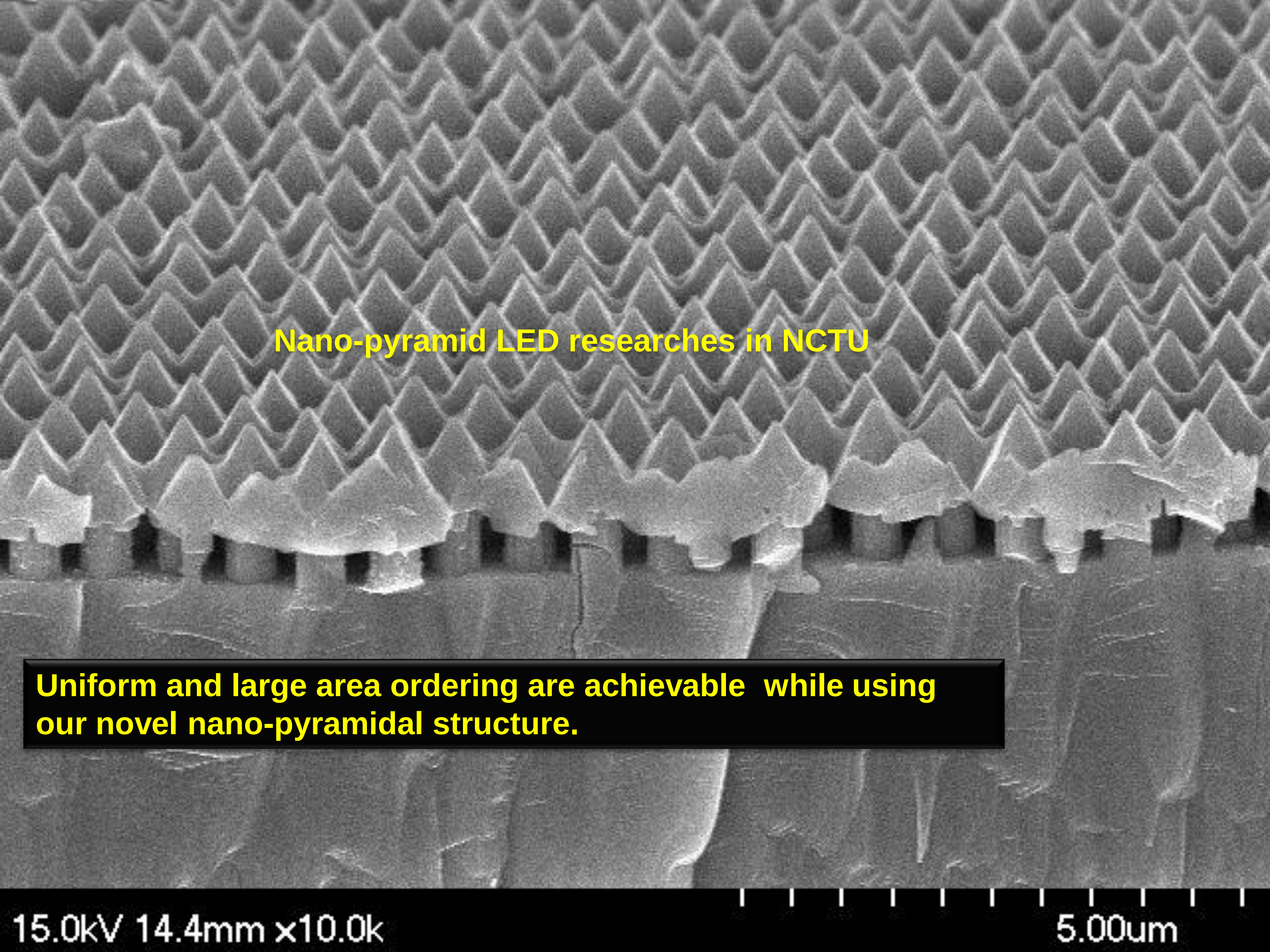
•**Nanostructures can be grown on Si or other low cost substrates to further reduce the cost.**

[1] S.P. Chang, H.C. Kuo et al, Appl. Phys. Lett. 100, 261103 (2012).
[2] S.P. Chang, H.C. Kuo et al, OPTICS EXPRESS, Vol. 20, No. 11, 12457 (2012).
[3] S.P. Chang, H.C. Kuo et al, Appl. Phys. Lett. 100, 061106 (2012)
[4] S.P. Chang, H.C. Kuo et al, OPTICS EXPRESS (2013)

Sample Preparation



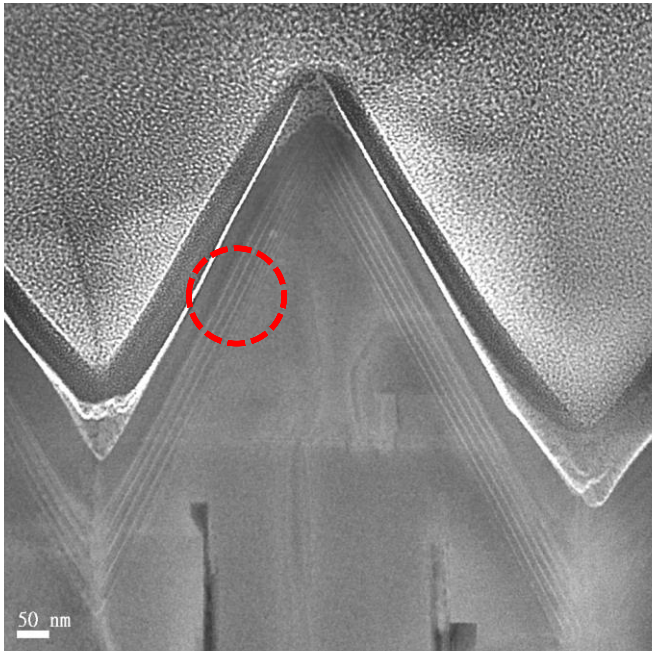
Nano-pyramid LED researches in NCTU

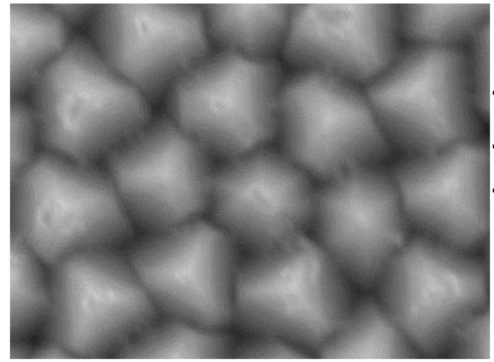


Uniform and large area ordering are achievable while using our novel nano-pyramidal structure.

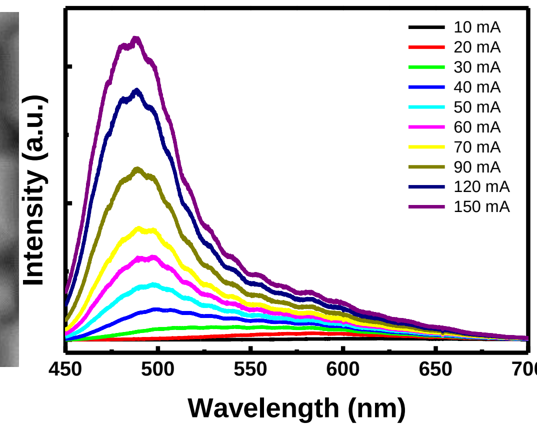
Cross section TEM image and CL of MQWs

Nano-pyramid MQWs



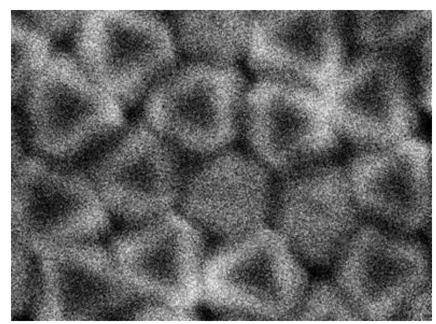


PQC

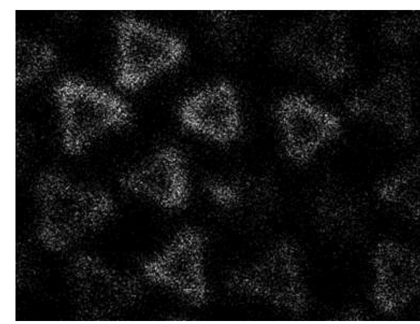


MQW	InGaN well	GaN barrier
Tg(°C)	830	910
Rg(A/s)	0.1	0.2
Nano-pyramid	3	12

CL @ 500 nm

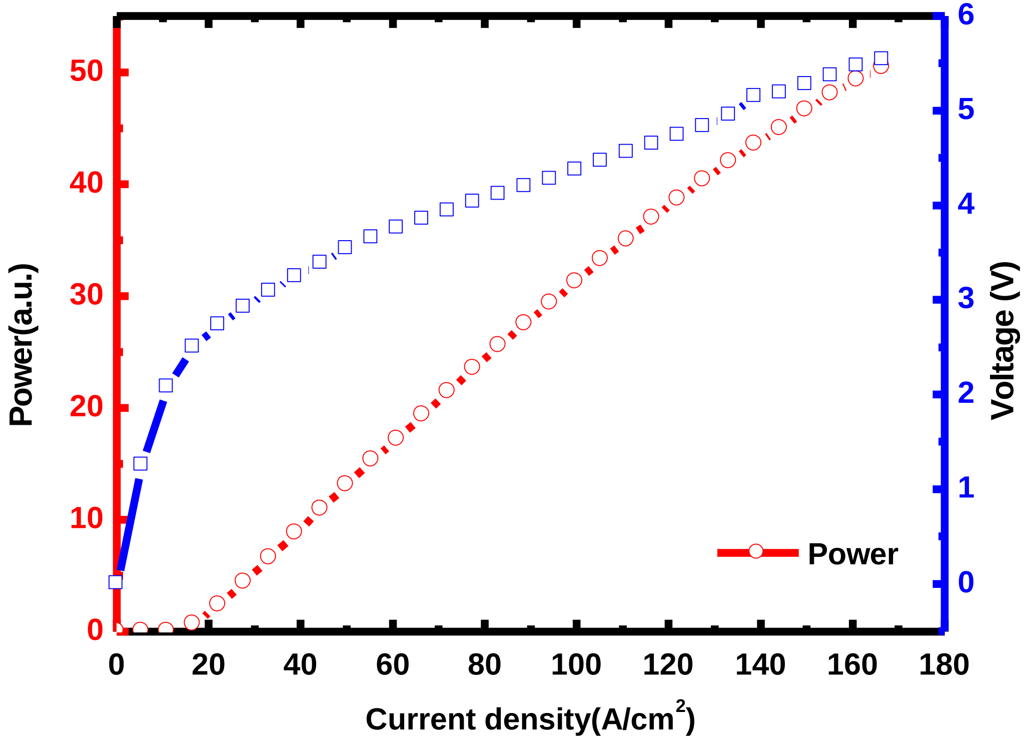


CL @ 560 nm



- **wavelength is longer at apex region –**
  In composition is higher at apex of pyramid
  QCSE is higher at apex.
- **Uniform composition along** semipolar {10-11} plane

LED device performance

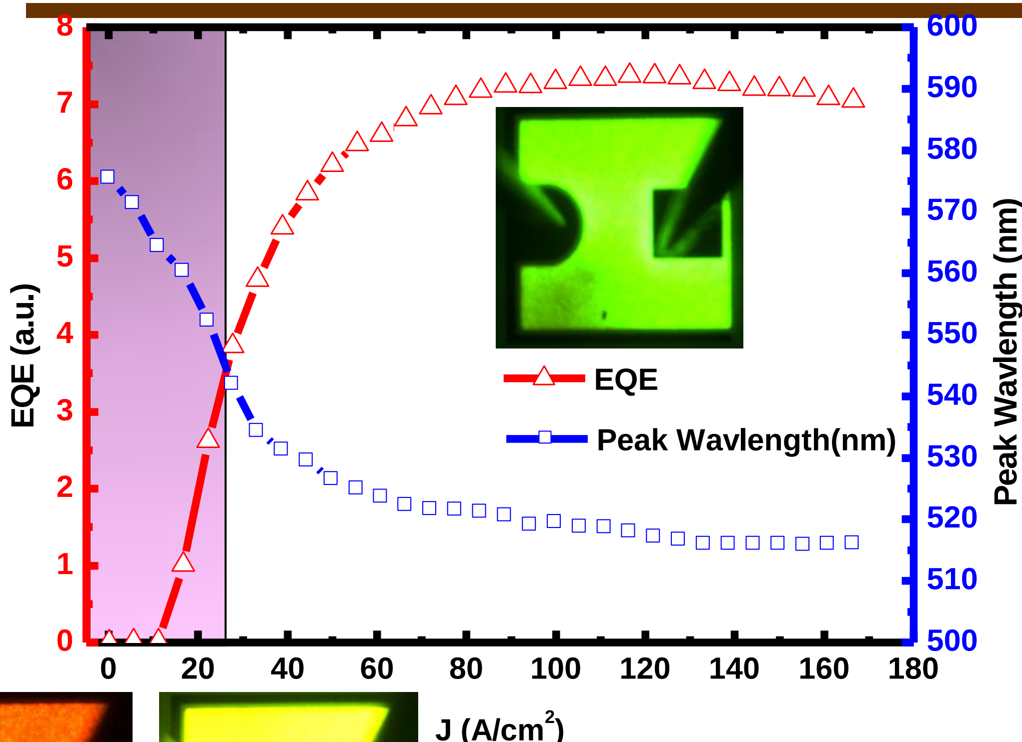


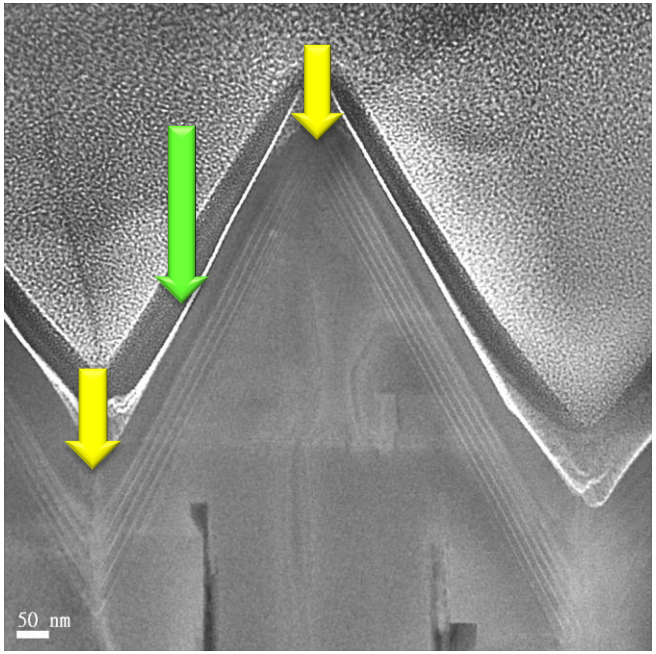
■The turn on voltage is about 2.5V@20mA, which is very close to the band gap of active layers.

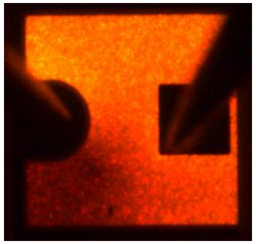
■The out put power linearly increases with injecting current even to the high injection level 160A/cm².

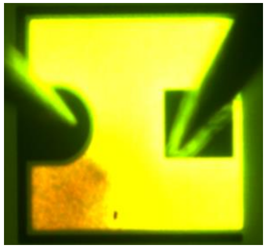
[1] H.C. Kuo et al, Appl. Phys. Lett. 101, 233104 (2012)

Efficiency **Droop** properties









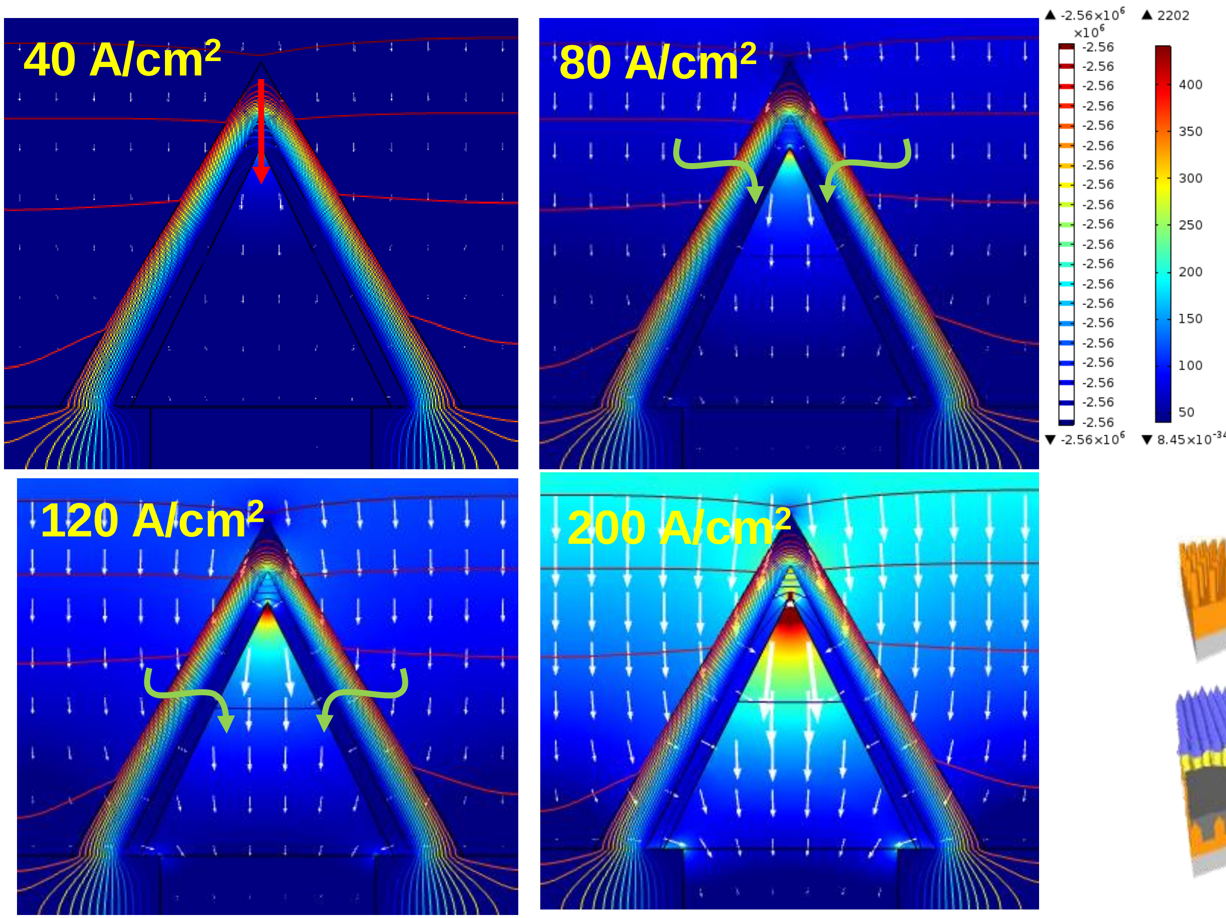
EQEMax~15%

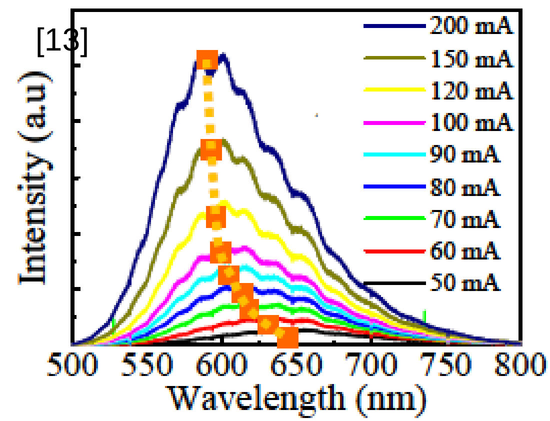
- **There is an intersection between efficiency and emission wavelength.**

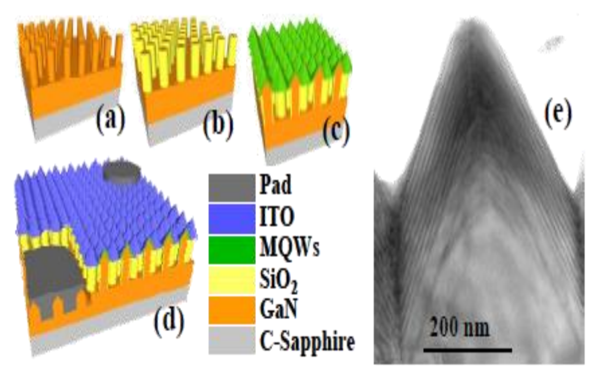
→inject at APEX then spread out along semipolar {10-11} plane

- **A stable and very low efficiency droop green emitter can be obtained after 40 A/cm^2.**

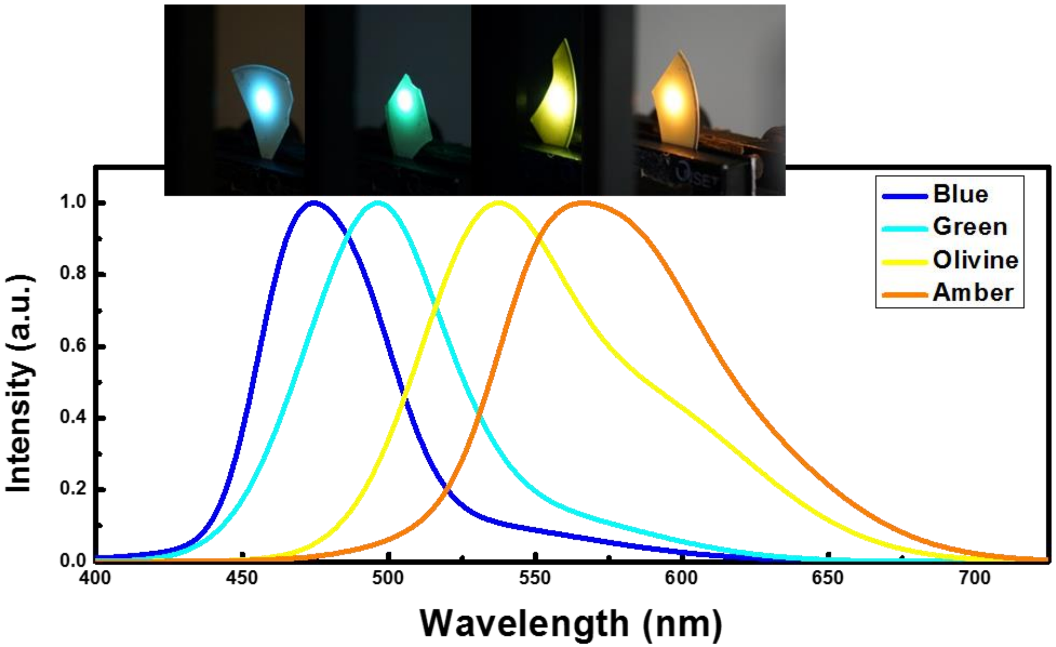
FEM simulation

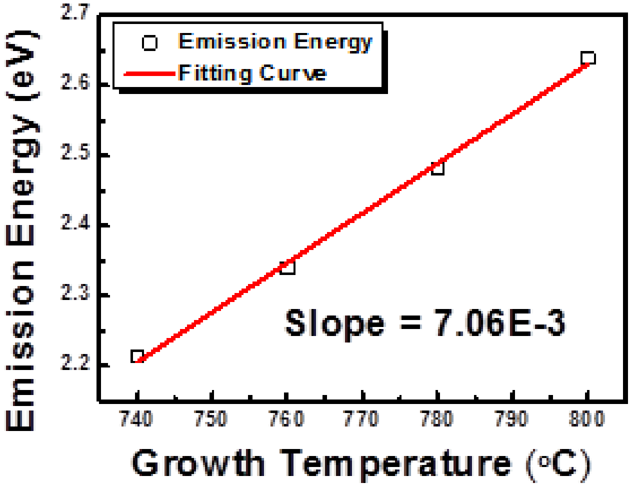






Emission Energy vs. Tg

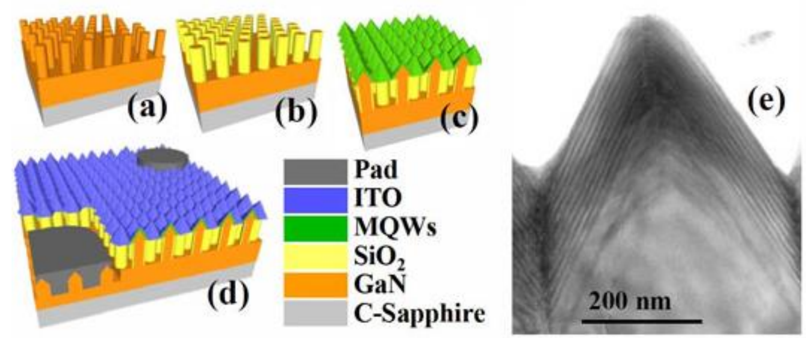


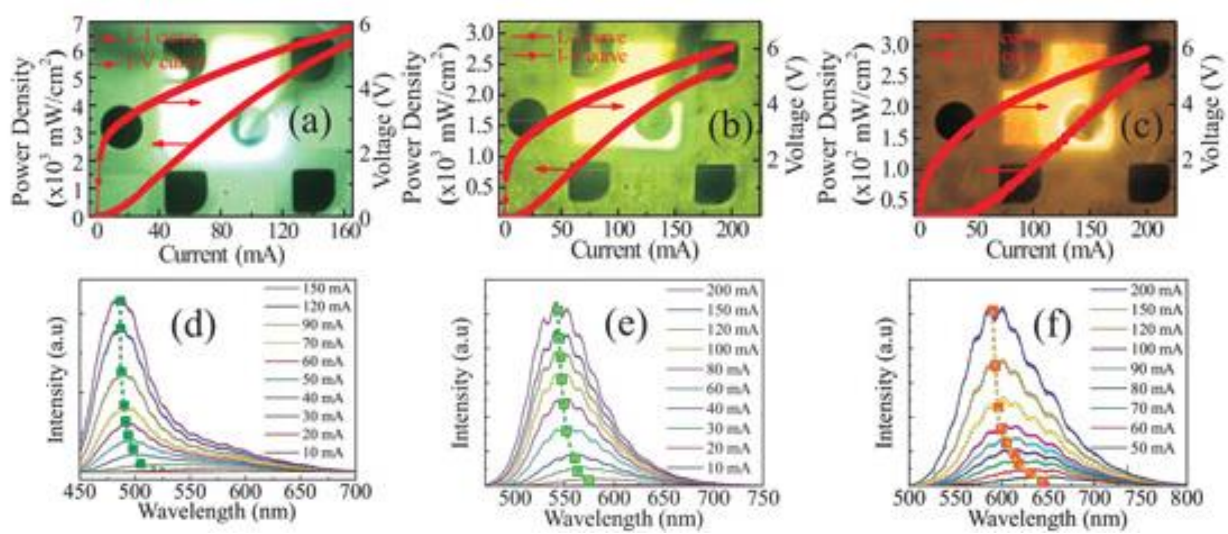


- **There is a high linear relationship between the emission energy and growth temperature on semipolar facet, the high In content for LEDs are available for various the growth temperature**

Exploring nanopyramid approach to longer-wavelength nitride LEDs

semiconductorTODAY
COMPOUNDS & ADVANCED SILICON





Bridging the amber-green gap and white LEDs

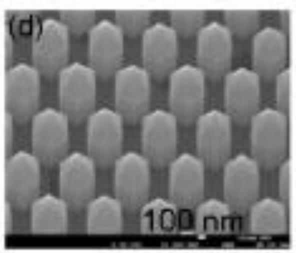
Mike Cooke reports on recent reports of various techniques to create light-emitting diodes that could fill the chasm, possibly leading to whiter LEDs.

Nanowire LED commercialization/Industry efforts

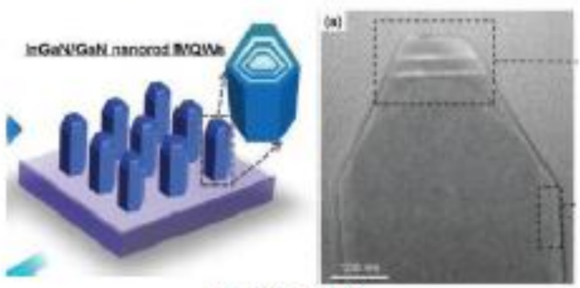
Industry/University Collaborations

- Epistar and National Chiao Tung University
- Osram Opto and Braunschweig U. Tech
- Samsung and Seoul National University

All focusing on bottom-up nanowires with core-shell (radial) MQWs

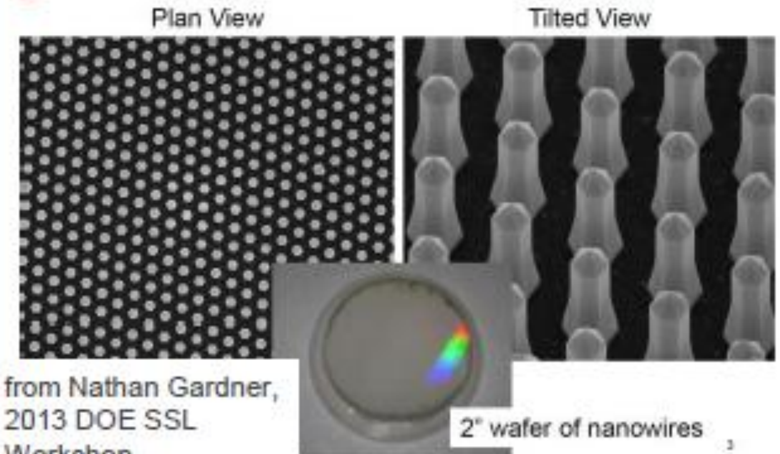


C.C Yang, 2012



G.C. Yi, 2011

glō
- Spun out of Lund University, Sweden
- Engineering Center in Sunnyvale, CA



from Nathan Gardner, 2013 DOE SSL Workshop

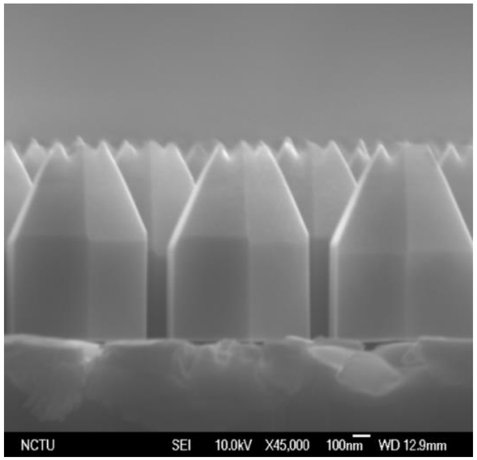
Bottom-up grown nanowires with *m*-plane MQWs

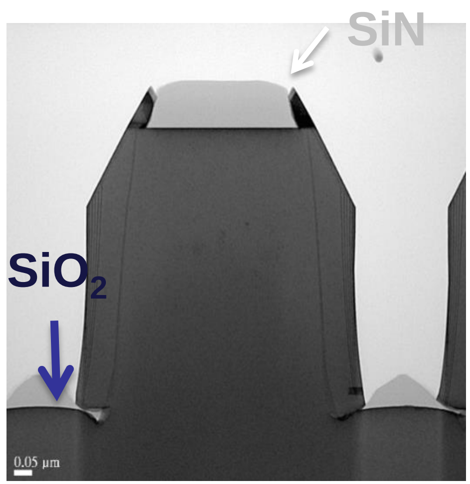
seren photonics
- U. of Sheffield start-up in 2010
- Top-down etched nanowires with Ag or Au nanoparticles deposited on sidewalls for plasmon coupling enhancement

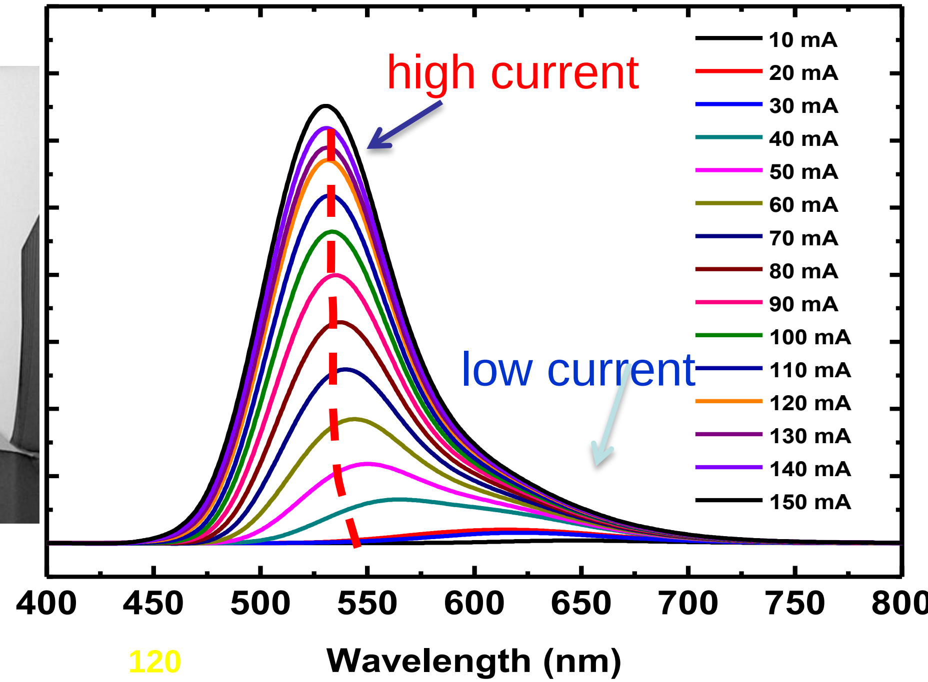
HelioDEL – spun out of LETI, Grenoble, France

George T. Wang, tSSL 2013

Coreshell LED by NCTU/Yale U

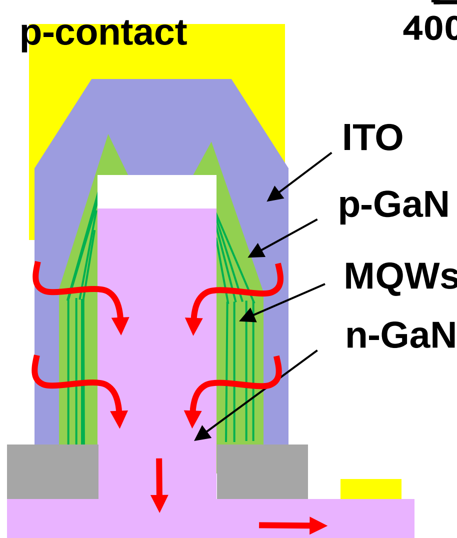


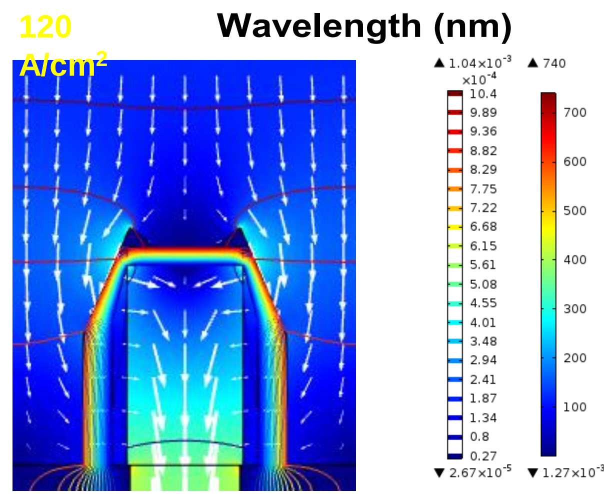




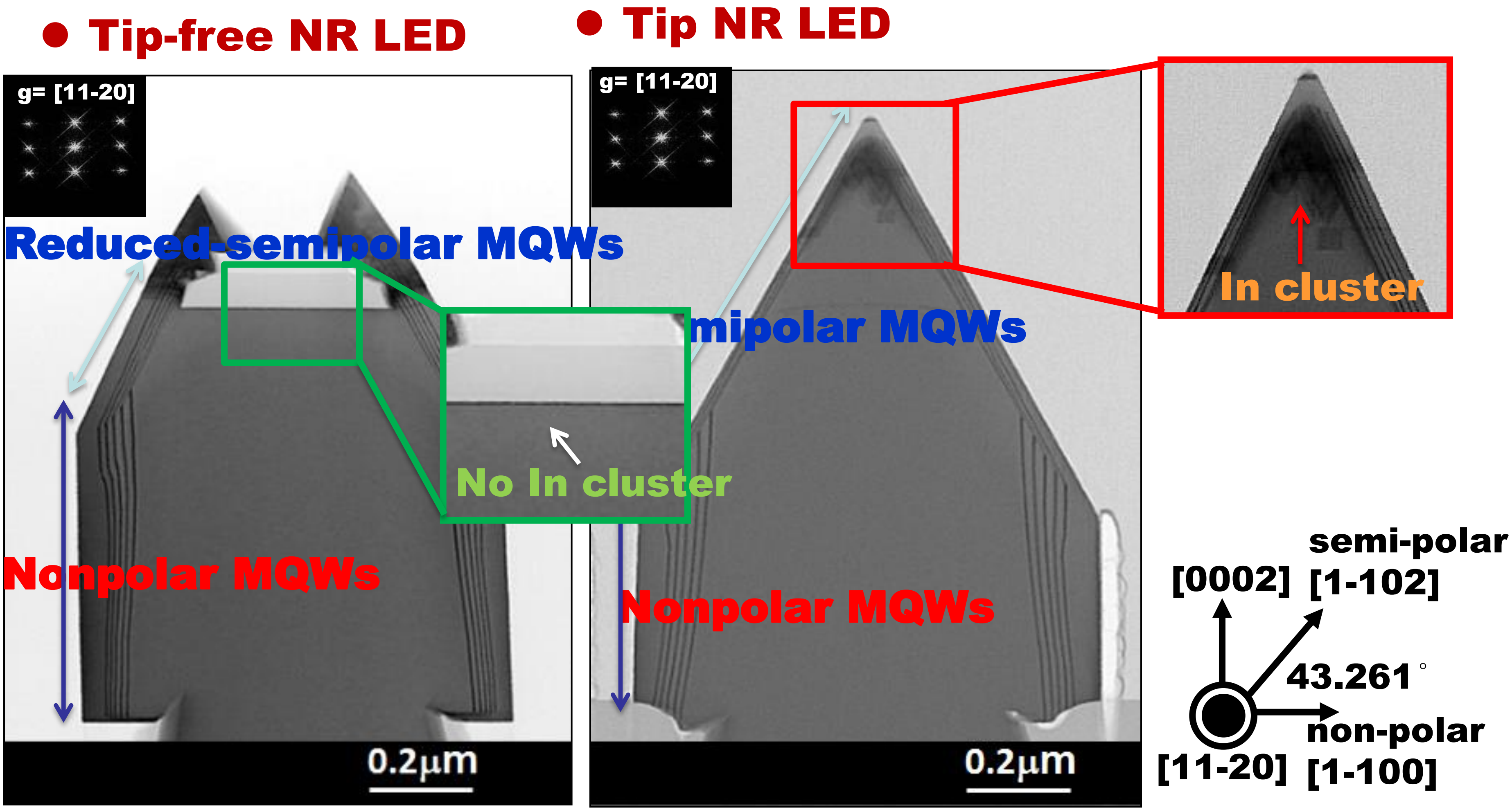
GaN on Si or Sapphire
Flexible substrate
Graphene

Graphene



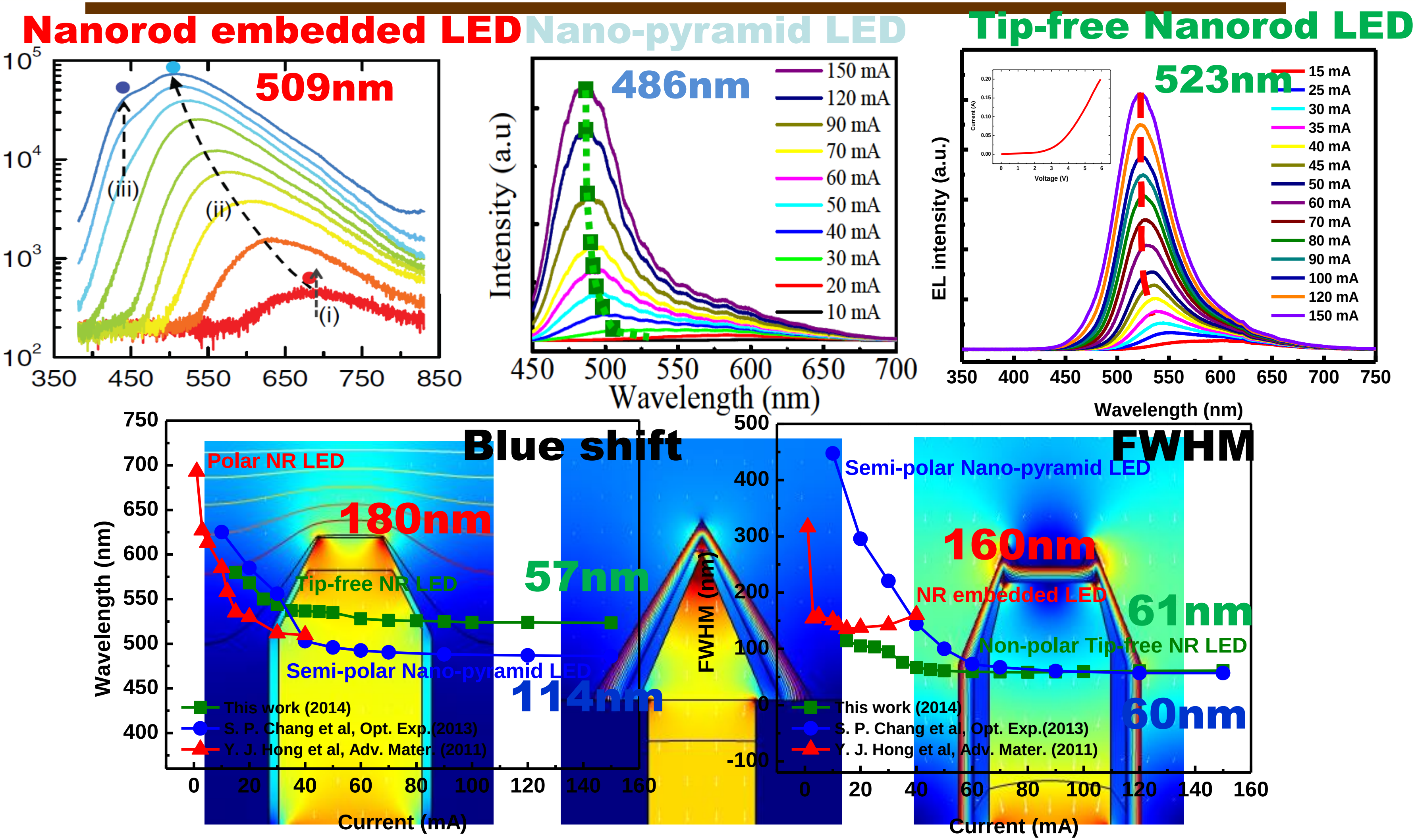


Transmission Electron Microscope (TEM) Measurement



- **Tip-free NR was fabricated and MQWs are formed both on semi-polar and non-polar plane.**
- **The area of semi-polar MQWs could be decreased by SiNx passivation.**
- **The formation of In clustering was prevented.**

Benchmark & Summary

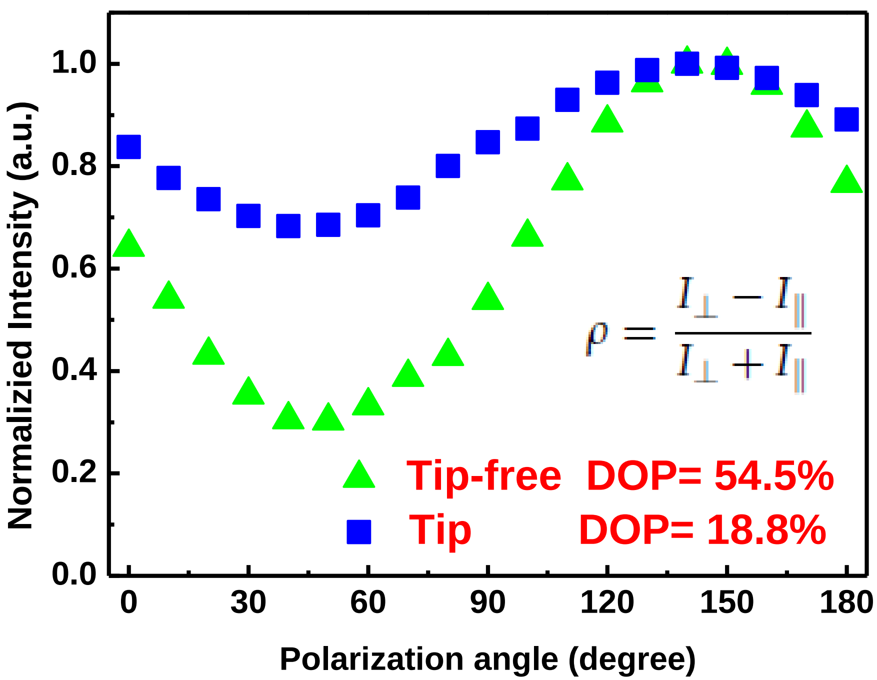


- **The smaller blue shift of EL peak of tip-free NR LED can be attributed to the improvement of In clustering on the top of nanorods and elimination of semi-polar MQWs.**

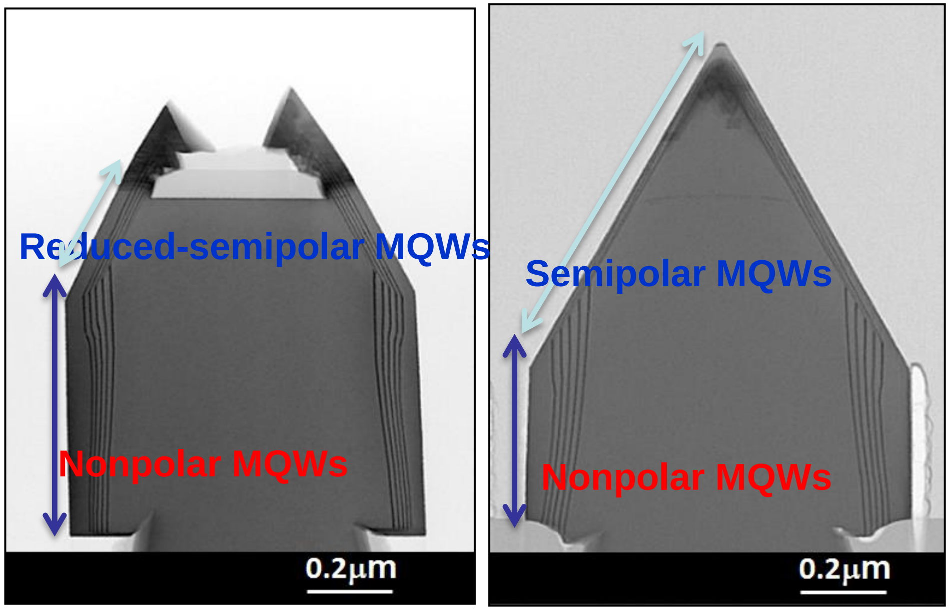
Results and Discussion

Linearly polarized PL measurement

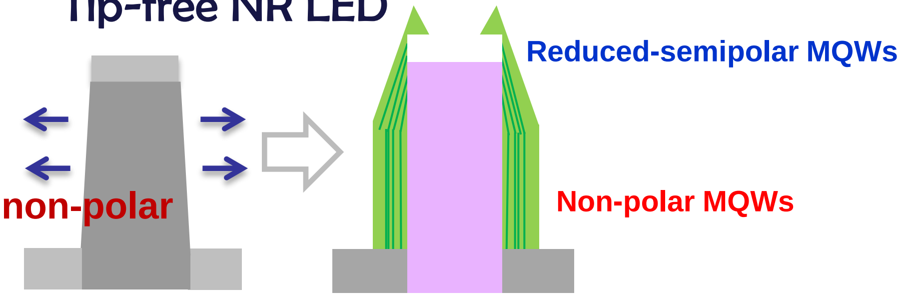
Degree of Polarization (DOP)



- Tip-free NR LED
- Tip NR LED

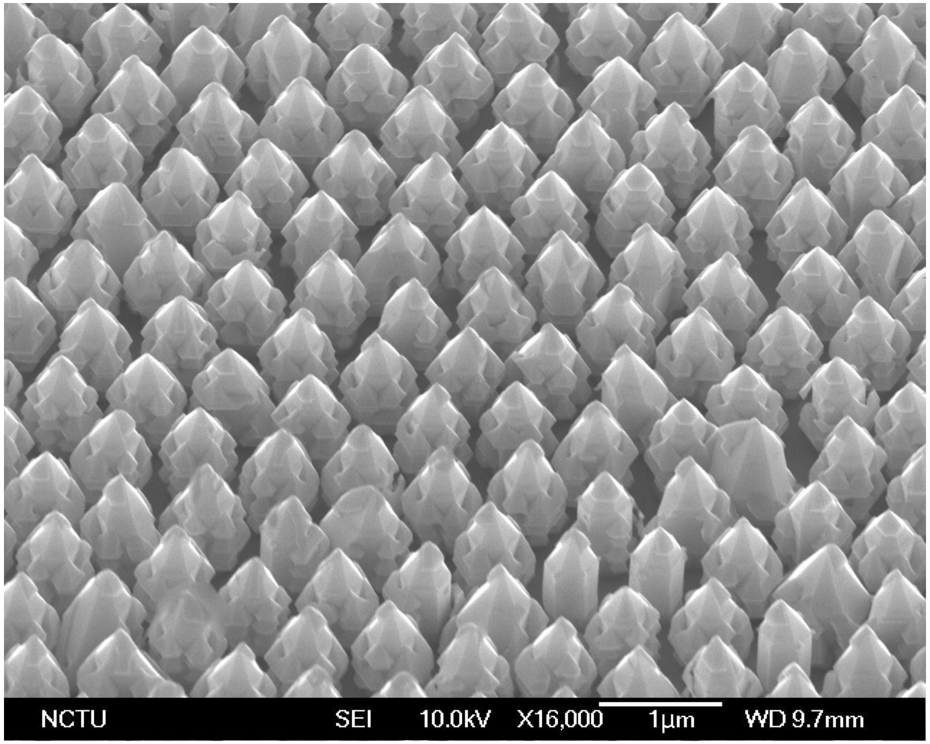


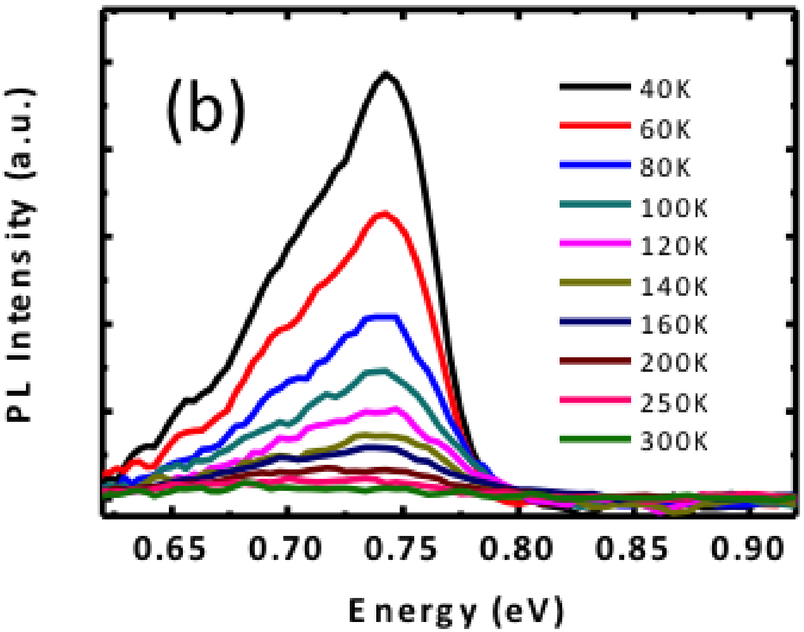
Tip-free NR LED

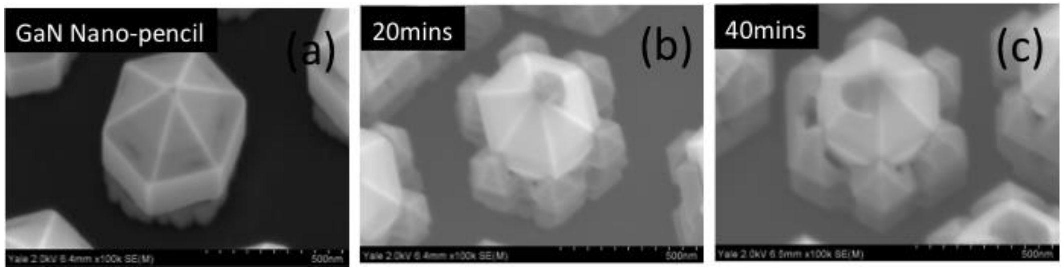


- DOP of tip-free and tip NR LEDs are 54.4% and 18.8%, respectively.
- The higher DOP was introduced by larger area of non-polar MQWs for tip-free NR LEDs.

InN nanostructure-for Solar cell or THz emission







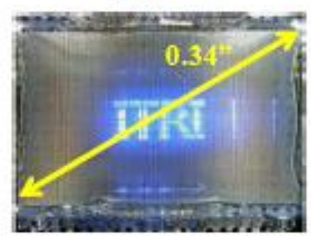
CLEO postdeadline paper 2014

Next killing application : Google glass/Apple/wearable

LuxVue Inc. Acquired by Apply May, 2014

LED on graphene/ITO

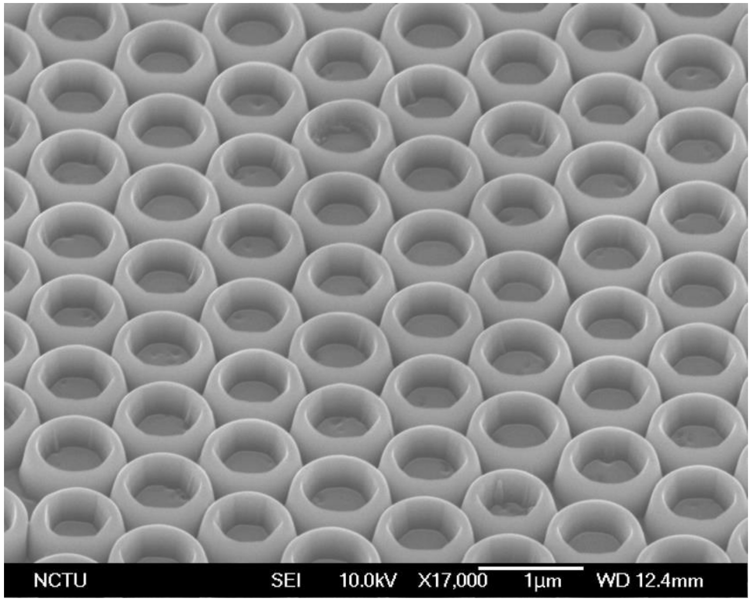
240x160 / 30 μm
single color

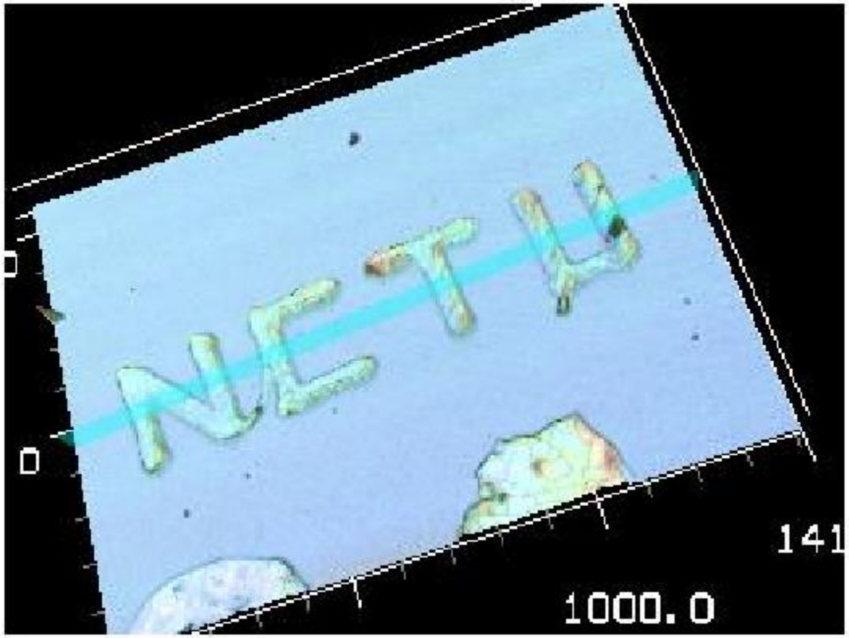


640x360 (12.8 μm)
single color

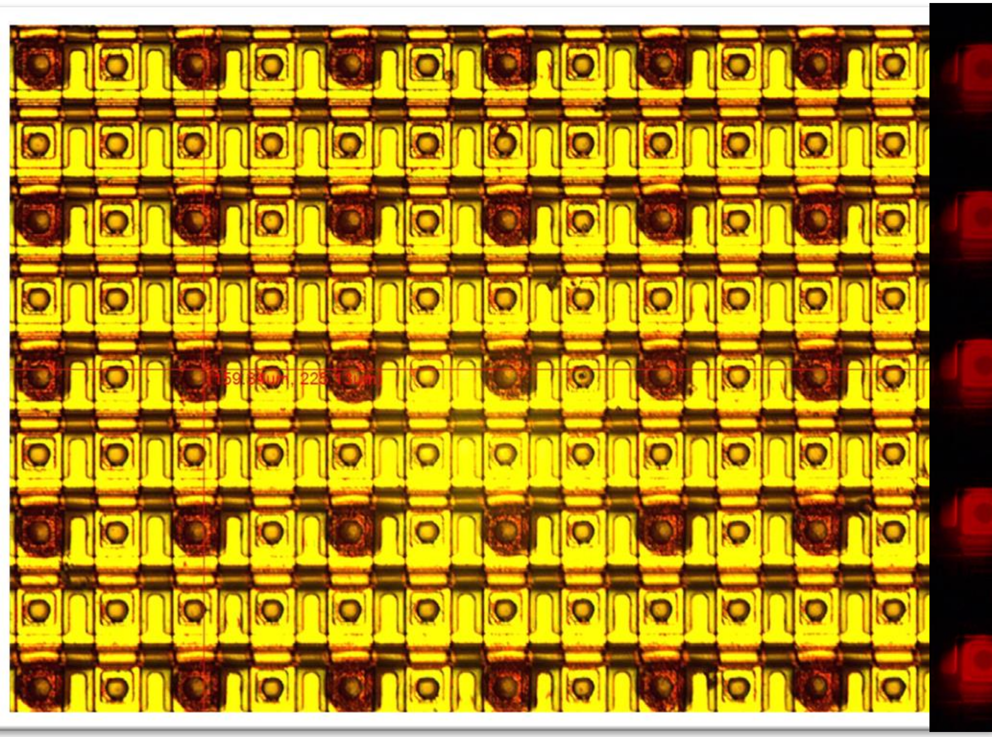
microdisplay

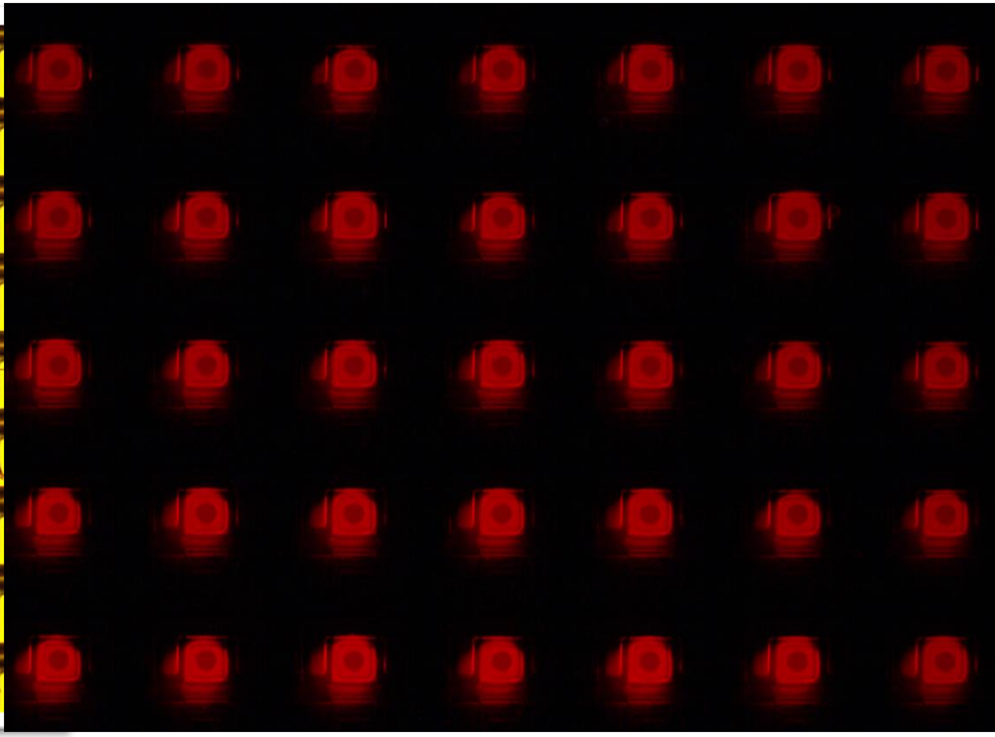
Nanoring LED/QD LED





Inkjet printing of QDs on micro-LED



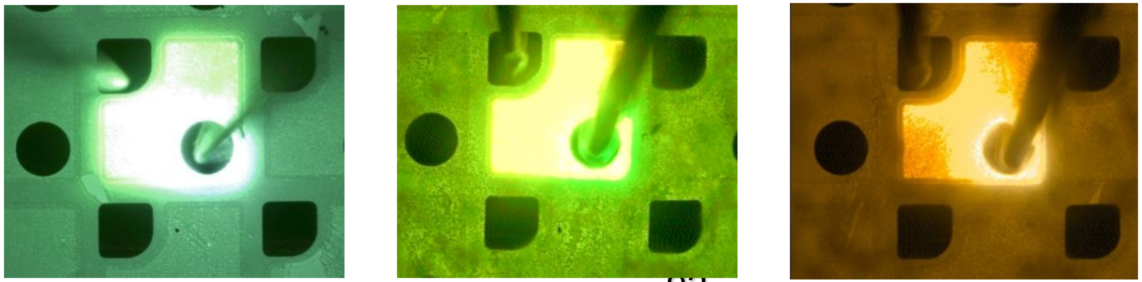


Conclusions

- LEE and current spreading improvement a lot for past few year (academic and industrial effort)

- The improvment of the **IQE** and **Droop –EBL design and material, Non-polar or semi-polar– good for LED and Laser**
  Green LED on c-plane sapphire still need to be improvement

- **The III-nitride nanopyramid LED should be a promising solution for full color emitter (fill green gap) and droop improvement**



Semiconductor Laser Lab

members (NCTU/NCKU) 4 professors 2 postdoc 30 students

S.J. Chang, Wei-Chih Lai (NCKU)

T.C. Lu, S.C. Wang , G. C. Chi, C.C. Lin, C. Y. Chang (NCTU)

Wide Bandgap Group: High Power GaN LED
Prof. S.C. Wang, H.C. Kuo

【經濟日報/記者李珣瑛／新竹報導】 2008.04.23 02:23 am

晶元光 ... 計畫，由晶電研發副總謝明勳（左起）、執行副總周銘
俊、交 ... ，要把LED發光效率倍數提高。
記者李

交大榮譽退休教授王興宗所率領的研發團隊，掌握將LED的效率會從目前的80流明／瓦（lm ／W），倍增到150lm／W的專利技術。LED龍頭大廠晶元光電（2448）昨（22）日與交大聯合舉行產學合作啟動典禮，宣布雙方將以二年時間，在磊晶及製程併進，提升發光效率到150lm／W目標。

LED產業在全球節能產業扮演要角，台灣LED上下游產業鏈完整，已占全球產量第二名。晶元光電將與交大進行更前瞻的「非極性發光二極體」相關研究，並針對光子晶體理論與元件作一完整的研究，將有利於加速固態照明的實現。晶電將優先取得與交大合作的研發成果，成為領先LED同業提升發光效率的利器。

晶元光電執行副總經理周銘俊表示，LED最受矚目的二大應用領域，主要是在顯示器的「背光光源」，以及「照明」的應用，而兩者發展的首要重點有賴LED發光效率的提升。

周銘俊指出，交大光電系所教授王興宗已掌握LED未取代燈泡、冷陰極管（CCFL），大幅提升LED效率的「密方」。晶元光電希望能夠結合交大光電系所這個擁有堅強實力的研究團隊，將研究資源與力量集中，在LED效率提升上有重大突破，共同促進LED產業向前邁進。

交通大學校長吳重雨指出，交大一向在產學合作的表現優異，去年高教評鑑中心針對大學產學合作績效的評鑑中，交大在「智權產出成果與應用效益」更居全國之冠，大幅領先群雄。

吳重雨表示，交大和晶元光電的合作計畫，就是產學合作的具體表現。

【2008/04/23 經濟日報】 @ http://udn.com/

Future work 180 lm/W->250 lm/W

2008/11/10

Thnaks for your support

International Collaborations

- 東京工業大學Prof. Iga及Koyama , UC Berkley Connie Chang 合作 – Photonics crystal and VCSEL design
- 史丹佛大學 Prof. Yamamoto, Prof. Fan合作 – Microcavity polariton laser
- HKUST – prof. KM Lau , Xiamen U – Prof. B.P. Zhang
- 耶魯大學Prof. Hui Cao, Prof. Han合作– Growth of non-polar GaN
- 壬色列理工學院Prof. Shawn-Yu Lin合作– Photonics crystal design, EF Shubert –LED Droop
- 日本京都大學Prof. Noda合作– Photonics crystal surface-emitting lasers
- 英國南安普敦大學(University of Southampton)- Dr. Martin D. B. Charlton合作- Cu(In,Ga)Se_2 Solar Cells

Domestic Collaborations

- 中央研究院應用科學中心程育人教授(Ph.D. Stanford)合作– Cavity quantum electro-dynamics (CQED)
- NDL 謝嘉明 博士 - High efficiency Solar cell
- 交大電子所張俊彥教授–High efficiency UV LED
- 工研院電光所– High-quality GaN substrate; 工研院綠能所 - High efficiency Solar cell

Industrial Collaborations

EPISTAR SAS Veeco TSMC

LITEON SUMITOMO OPTORUN KLA Tencor

SCI paper and conference 2009-2013

Journal Paper x 90

- ACS Nano x 2
- **Advanced Material x 2**
- **Advanced Energy Material x 1**
- **Advanced Functional Material x 1**
- **Nano Letters x 2**
- **Solar Energy Materials and Solar x 5**
- Journal of The Electrochemical Society x 2
- IEEE J. Select. Topics Quatum Electron x 4
- IEEE Electron Device Lett. x 3
- **Appl. Phys. Lett. x 12**
- Journal of Applied Physics x 3
- **Optics Express x 10**
- IEEE J. Select. Topics Quatum Electron. x 4
- JOURNAL OF LIGHTWAVE TECHNOLOGY x 2
- **IEEE PHOTONICS TECHNOLOGY LETTERS x 12**
- NANOTECHNOLOGY x 3
- APPLIED PHYSICS EXPRESS x 4
- JAPANESE JOURNAL OF APPLIED PHYSICS x 10

Conference Paper x 50

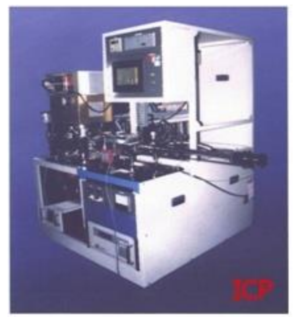
- SPIE Proceedings x 10
- 4 invited talk
- The Conference on Lasers and Electro-Optics (CLEO) x 20
- **Two CLEO post deadline**
- one invited talk
- IEEE International NanoElectronics Conference x 2
- Conference on Lasers and Electro-Optics (CLEO/PR) x 10

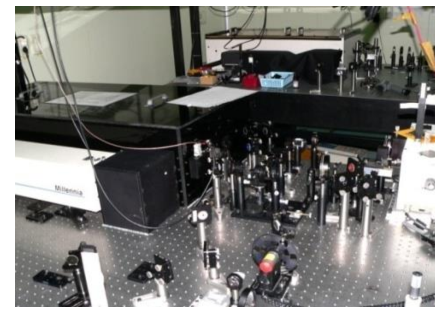
Thanks for your attendtion

Photonics -Equipments for LEDs and VCSEL

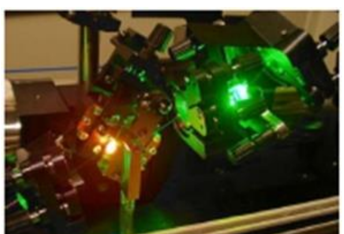
磊晶 x2

奈米製程



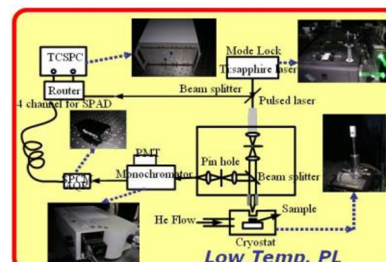


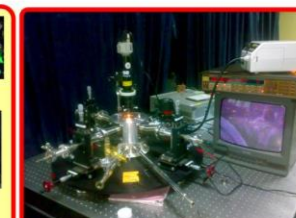
光電特性及熱效應量測



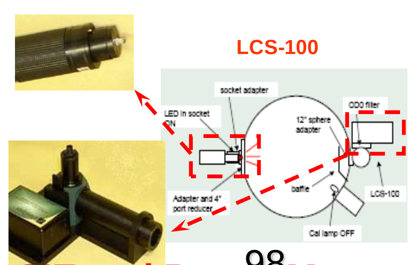
Ti: sapphire laser

J T Meas. system





IQE system



CIE and Power Meas.

Nanorobotics Manipulator