Recent Performance of Nonpolar/Semipolar/Polar GaN-Based Blue Emitting Devices and GaN bulk Crystal Growth

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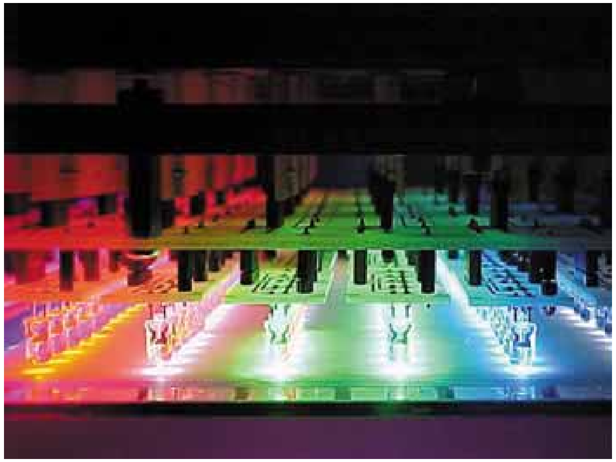
1. *Introduction*

2. *Latest Performance of Nonpolar/Semipolar LEDs and LDs*

3. *Bulk GaN Growth by Ammonothermal Method*

The Advantage of LED Lighting

Long life – lifetimes can exceed 100,000 hours as compared to 1,000 hours for tungsten bulbs



Robustness – no moving parts, no glass, no filaments

Size – typical package is only 5 mm in diameter

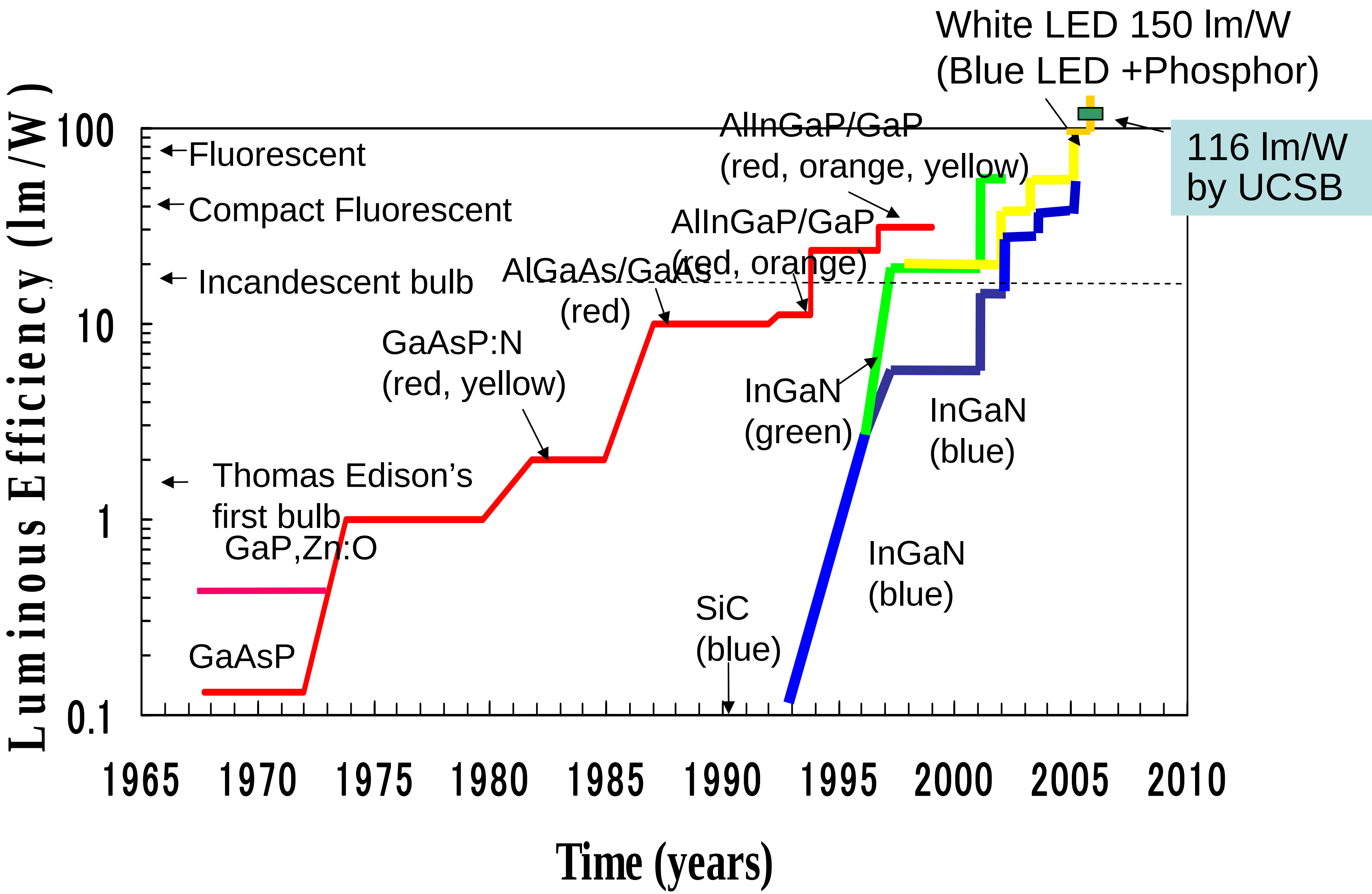
Energy efficiency – up to 90% less energy used translates into smaller power supply

Non-toxicity – no mercury

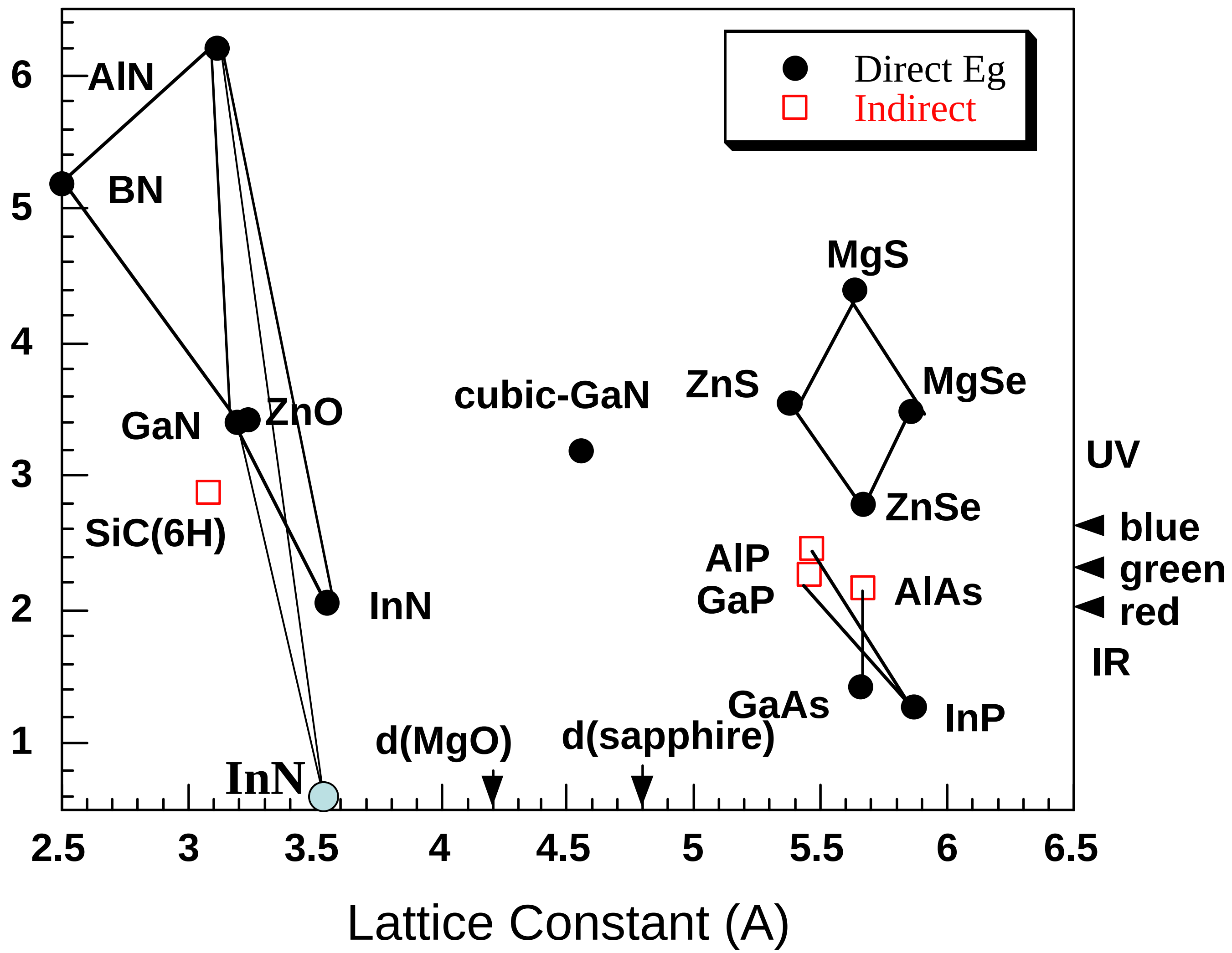
Versatility – available in a variety of colors; can be pulsed

Cool – less heat radiation than HID or incandescent

GaN LED Historical Development

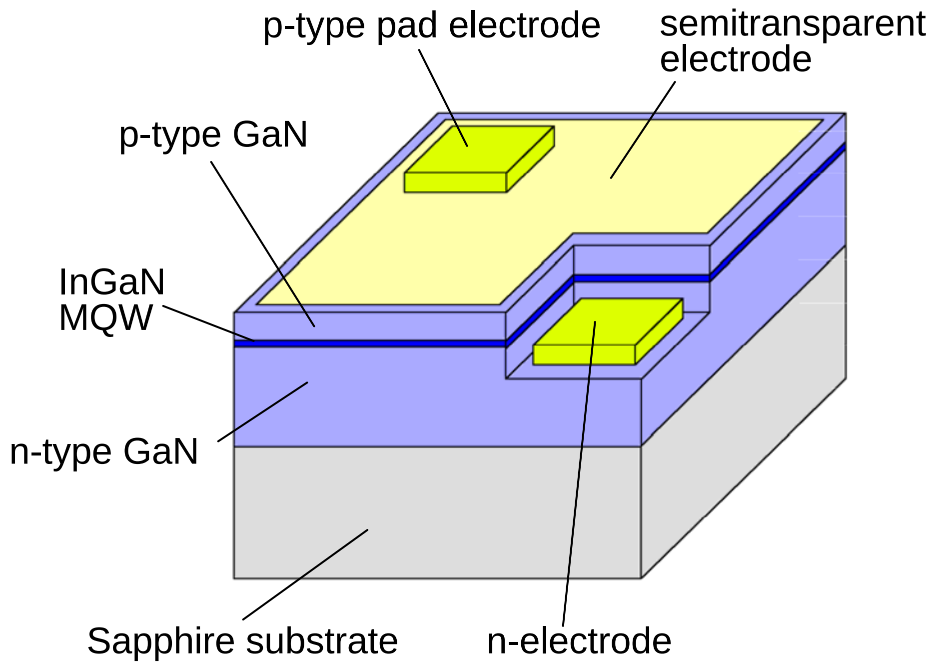


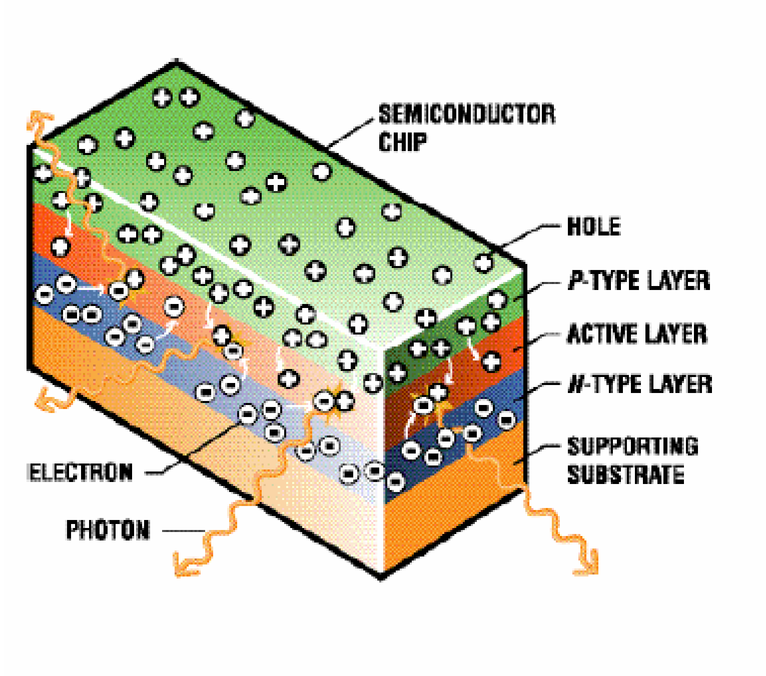
WIDE BANDGAP RANGE



Eg(InN)~0.7

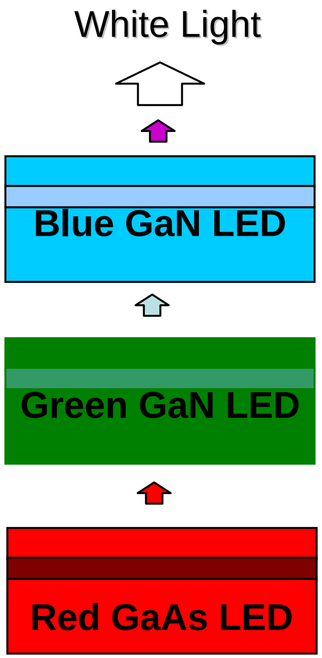
Typical Blue LED Structure on Sapphire



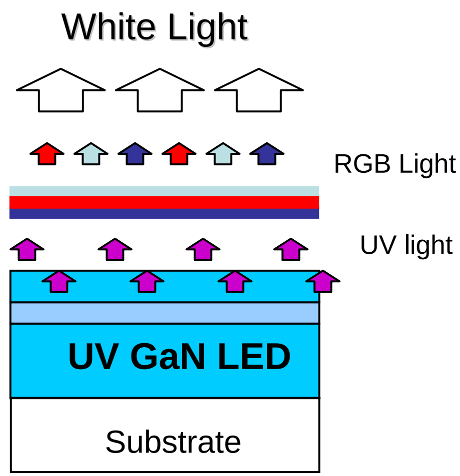


Blue LED produces light by combining positive and negative charges inside gallium nitride crystal

3 Methods of Generating White LEDs

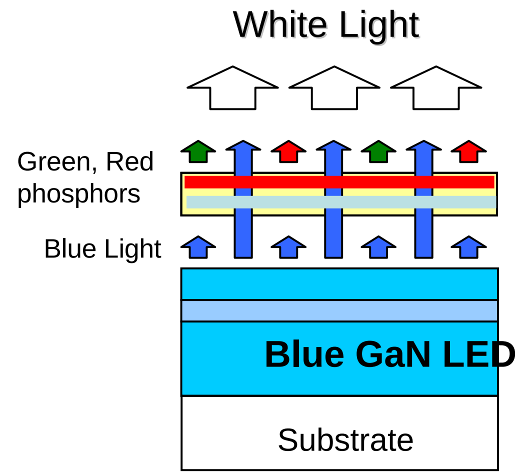


<u>Multi-Chip, RGB</u>
- good efficiency
- highest cost
- tunable color



<u>UV + Phosphors</u>
- best CRI,
- color uniformity
- low cost
- improve reliability

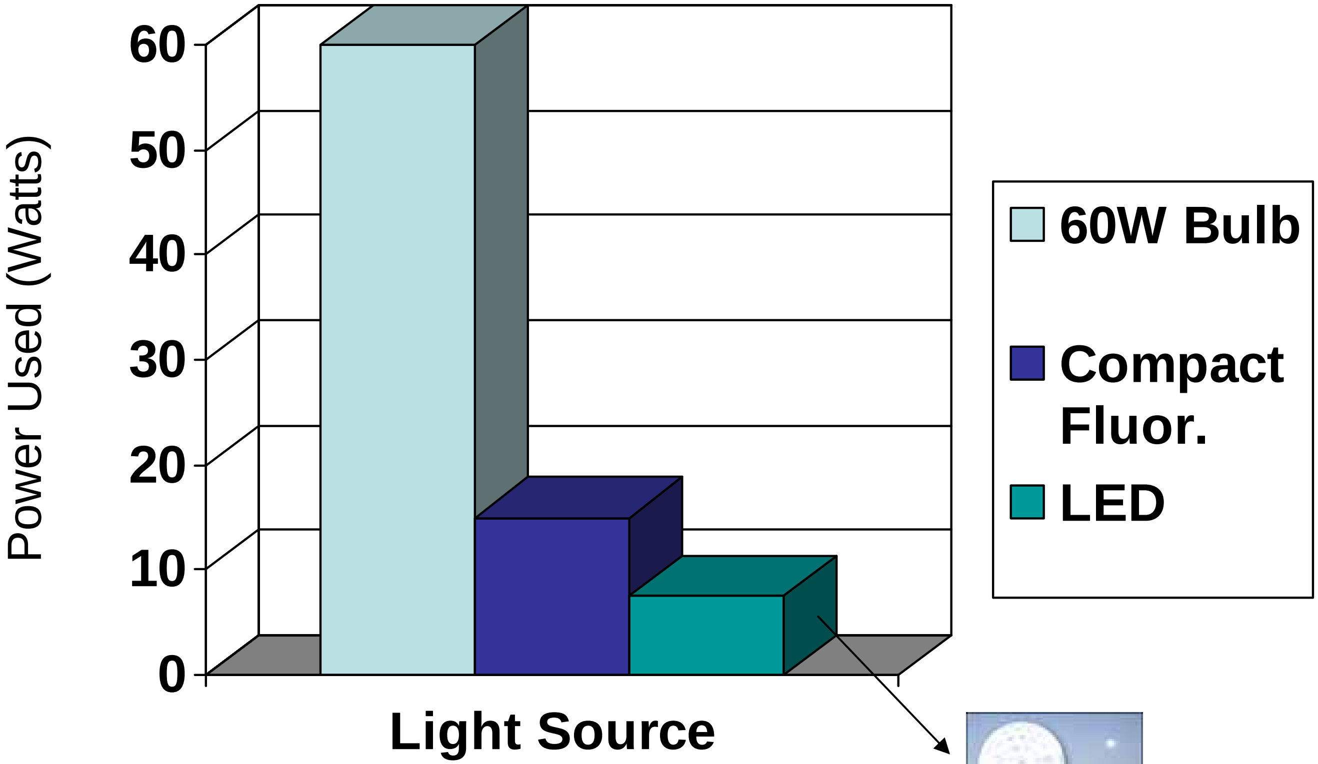
100 lm/W (2005)



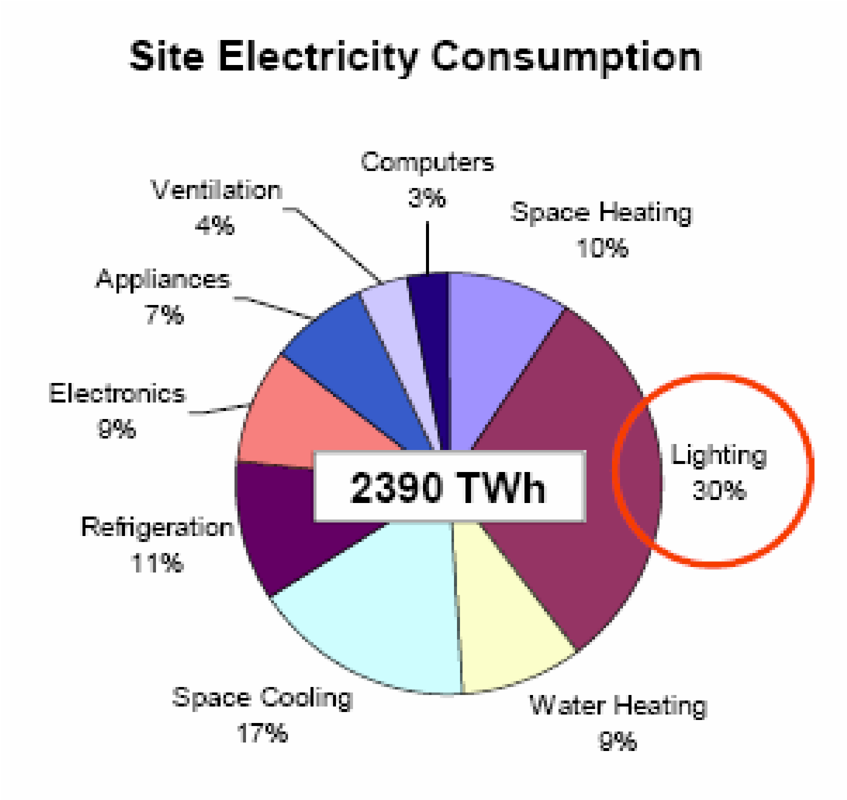
<u>Blue + Phosphors</u>
- lowest cost
- 100 lm/W
- 90% market share

“The Promise” Energy Usage Comparison

“Best” White LED and Compact Fluorescent vs. 60Watt Light Bulb Comparison



Lighting: Large Electricity Consumption



Lighting is single biggest user of electricity

- Incandescent Light Bulb -1-4% efficient
- Fluorescent – 15-25% efficient
- LED- 25-52% efficient (90% theoretical)

Outdoor

Light Up The World Foundation

www.lutw.org

- Kerosene lighting and firewood are used by 1/3 of the world; they cause countless fires and are very inefficient (0.03 lm/watt).
- The average villager spends 10-25% of their annual income on kerosene.
- LED Lighting costs much less on an annual basis and payback period is just 6 months.
- LED Lighting allows education at night and increases safety for the Third World.

"In the few months we have had the White LED lamps the improvement in the children's academic performance has been absolutely remarkable"

Headmaster, Mubarak Village, Pakistan June 2004

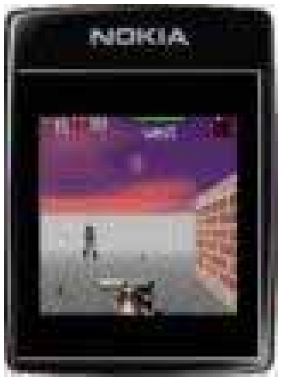
Global Warming/Energy Savings Potential of LEDs

If a 150 lm/Watt Solid State White source were developed, then in the United States alone:

- We would realize $115 Billion cum. Savings in 2025*
- Alleviate the need of 133 new power stations!*
- Eliminate 258 million metric tons of Carbon*
- Save 273TWh/year in energy**

*** "The Promise of Solid State Lighting" OIDA Report , 2001, http://www.netl.doe.gov/ssl/PDFs/oida_led-oled_rpt.pdf**
****A. D. Little, "Energy Savings Potential of SSL" Report for Dept. of Energy, http://www.eere.energy.gov/buildings/info/documents/pdfs/ssl_final_report3.pdf**

Current LED Applications



Cell Phone
(Nokia)

Traffic Signals
(Gelcore)

Large Displays
(NASDAQ)

Streetlights

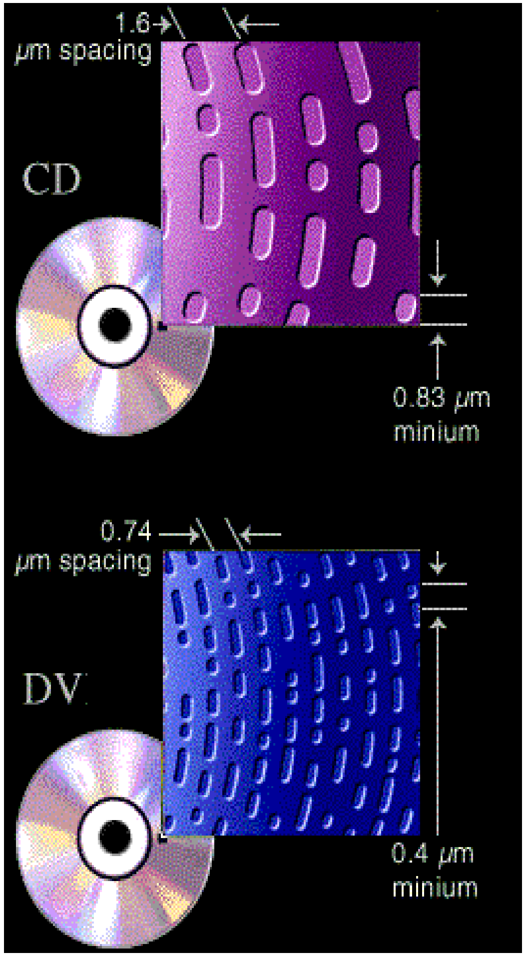
TVs (LED DLP^{tm})
(Samsung)

Automotive

GaN Lasers enables Blu-Ray and HD-DVD

- Next generation large capacity optical disc video recording formats called "Blu-ray Disc“ and “HD-DVD” for recording, rewriting and play back of up to 27 gigabytes (GB) of data will use 405nm blue-violet laser diode.

HD-XA1

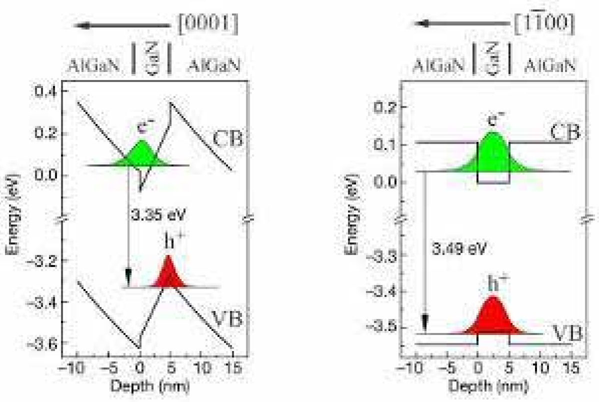


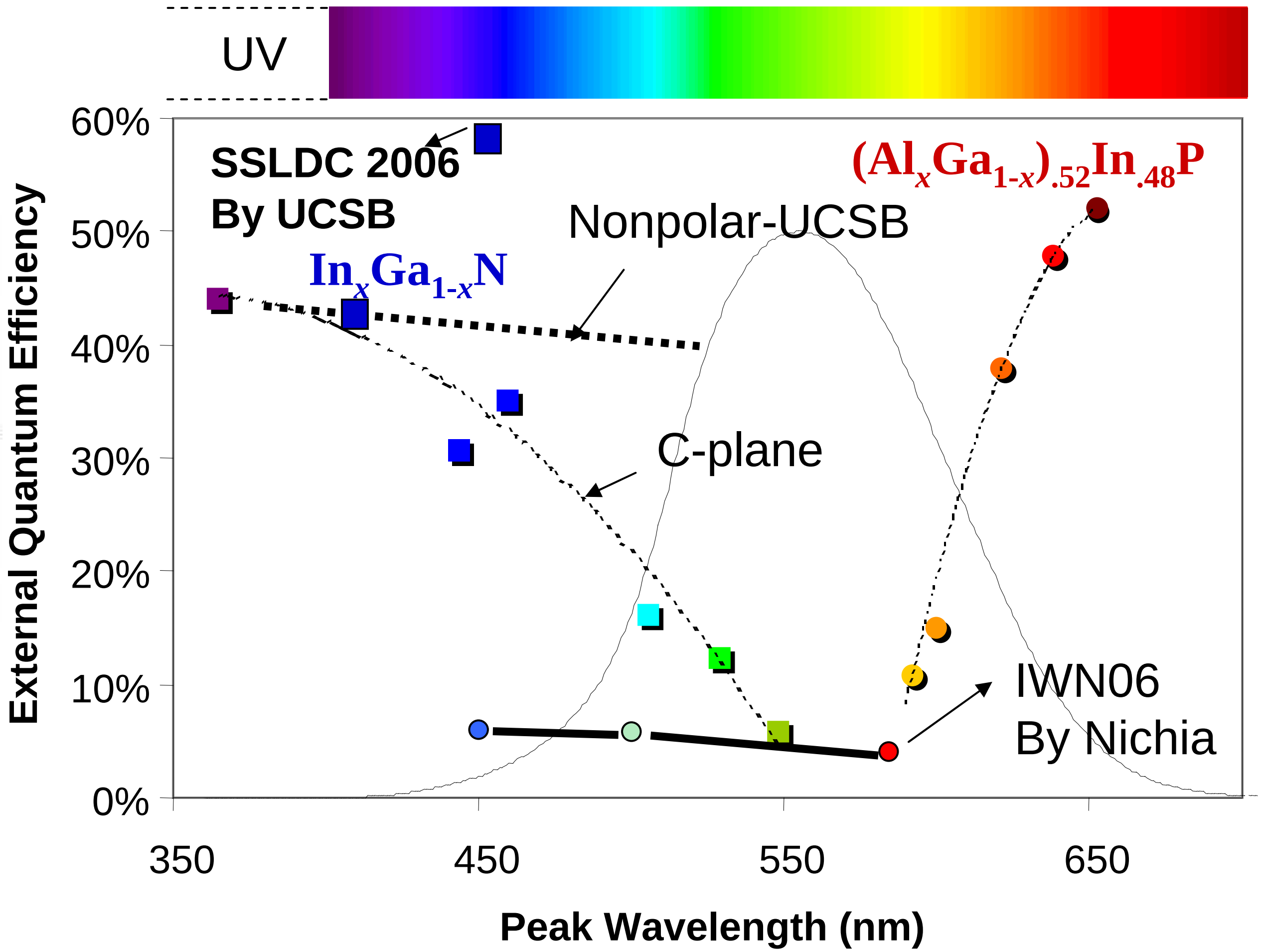
Optical Storage

	CD (IR)	DVD (red)	Blue-ray
Wavelength (nm)	780	650	405
Disc Diameter (cm)	12	12	12
Numerical Aperture	0.45	0.6	0.6
Track Pitch (μm)	1.6	0.74	0.42
Shortest pit length (μm)	0.83	0.4	0.27
Capacity of a single side, single layer disc	680 MB	4.7 GB	27 GB
Capacity of a two sided, dual layer disc	N/A	17 GB	54 GB estimate
Normalized Capacity	1	7	22

Non-Polar GaN: LED Efficiency vs. Wavelength

- Polarization fields in polar QWs create problems in **green, ultraviolet, can Nonpolar solve the green gap?**





Laser TV

Mitsubishi "Laser TV" with Arasor and Novalux components (left) and Plasma (right)

Future SSL Displays

Pocket Projector/Cell Phone

Prototype from Novalux using frequency double lasers

*μ*Cone-LEDs

Light Extraction Efficiency

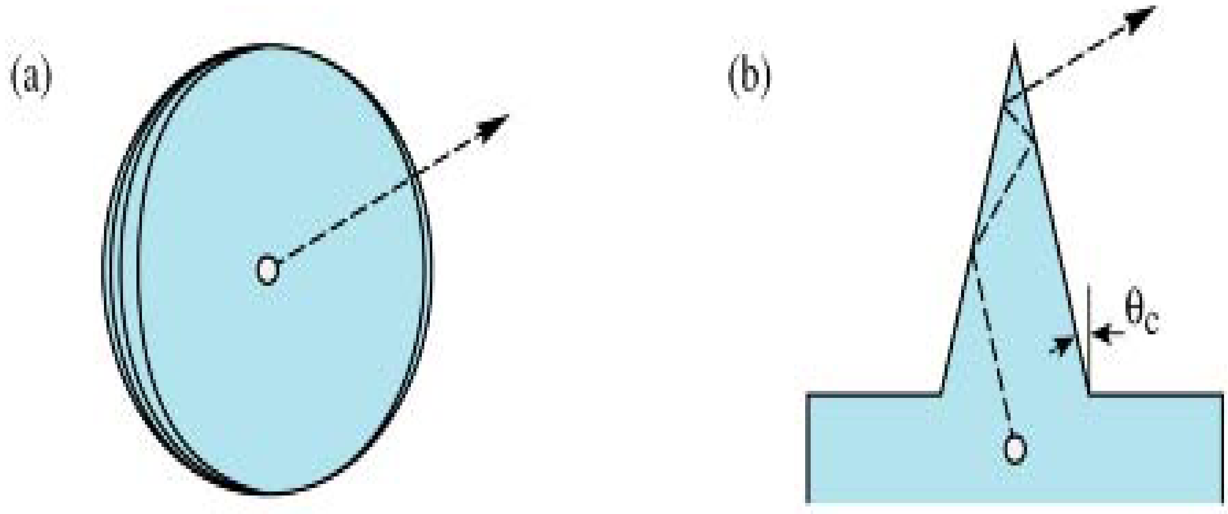
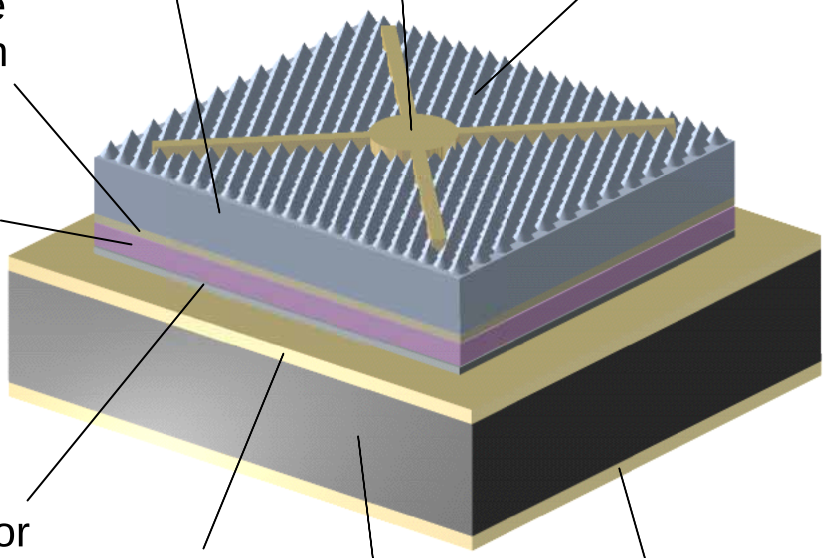


Fig. 6.4. Schematic illustration of different geometric shapes for LEDs with perfect extraction efficiency. (a) Spherical LED with point-like light-emitting region in the center of the sphere. (b) Cone-shaped LED.

µCone LEDs: Light Extraction by Roughening



- **No semitransparent electrode**
- **Reflective backside mirror**

  → **Increase in light extraction**

- **Lower thermal resistance than than sapphire substrates**

  → **High operating current**

- **Vertical current flow**

  → **Easy to scale up**

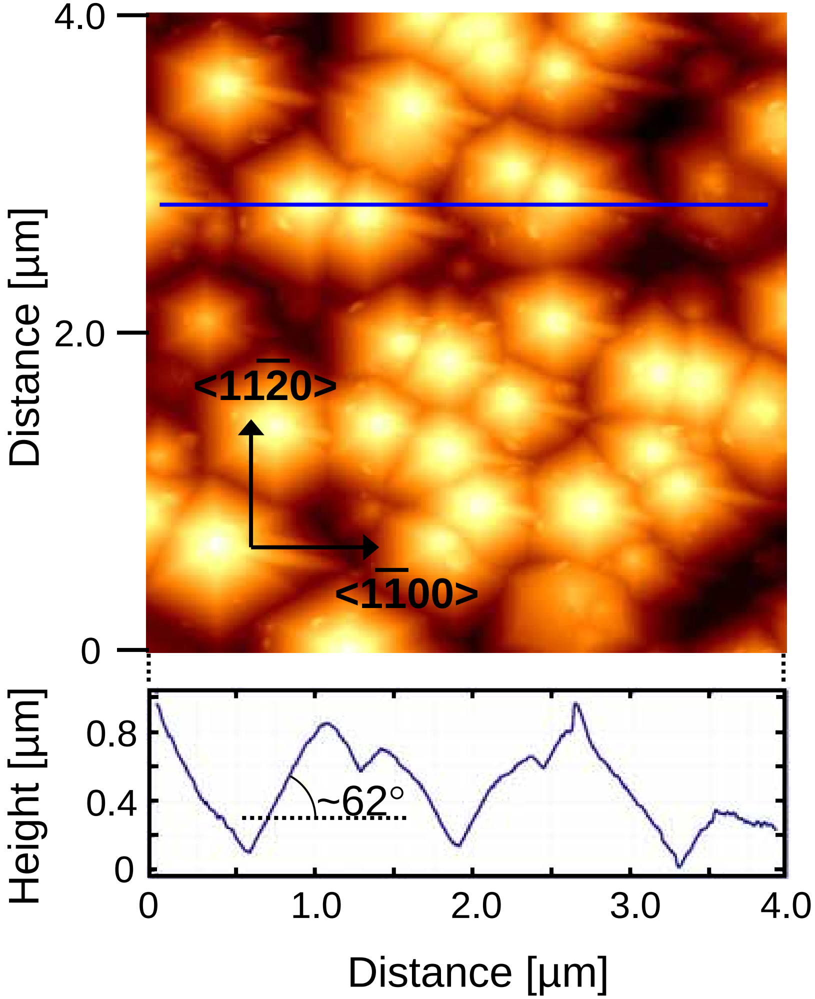
- **Cone-shaped surface features**

  → **Good for light extraction**

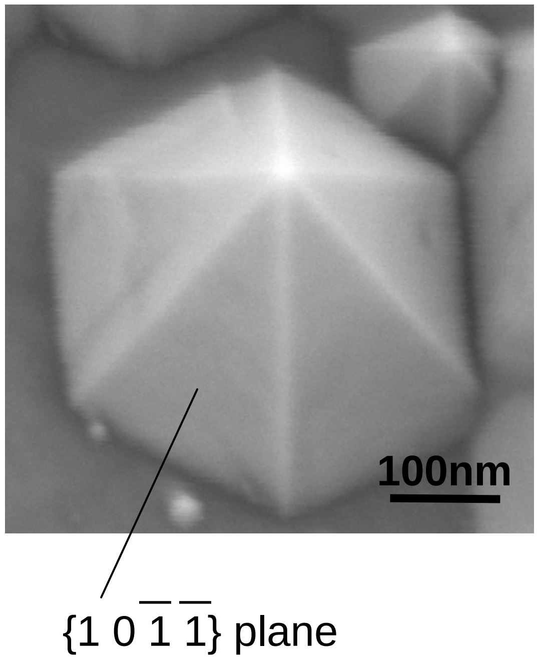
T. Fujii, Y. Gao, R. Sharma, E.L. Hu, S. P. DenBaars and S. Nakamura
Appl. Phys. Lett. 84 (2004) 855

Cone-shaped surface LED

AFM & SEM image

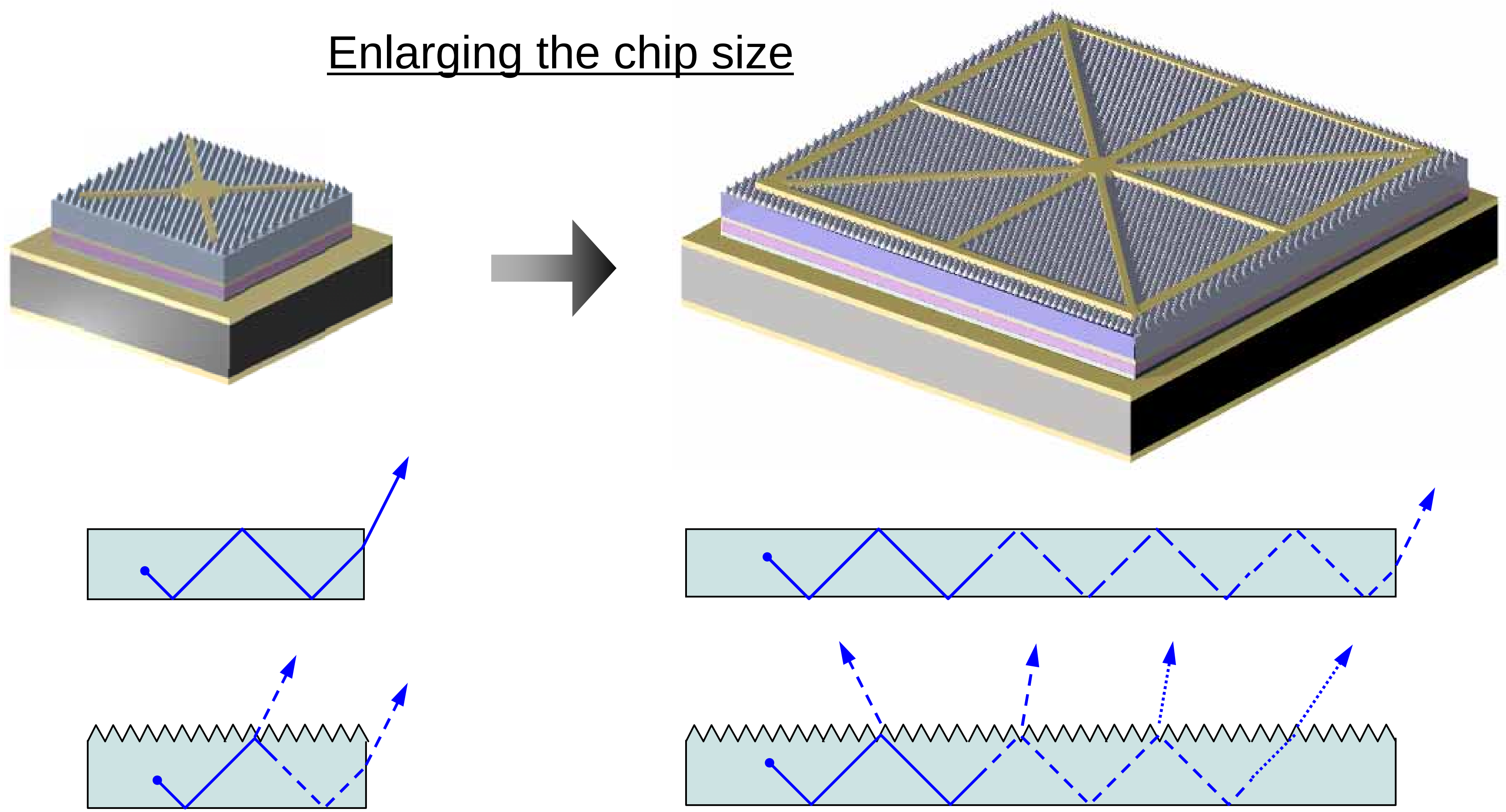


Hexagonal pyramid



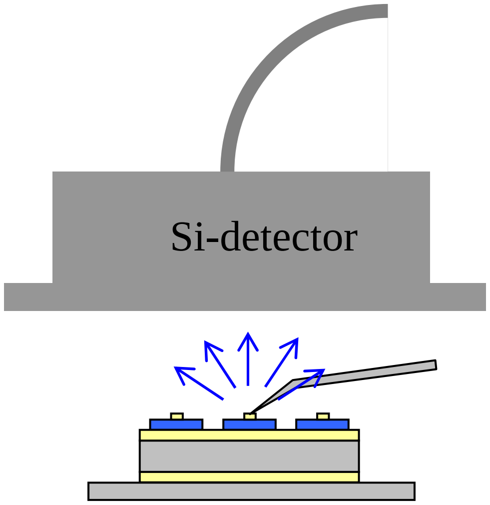
µCone LED Scalability

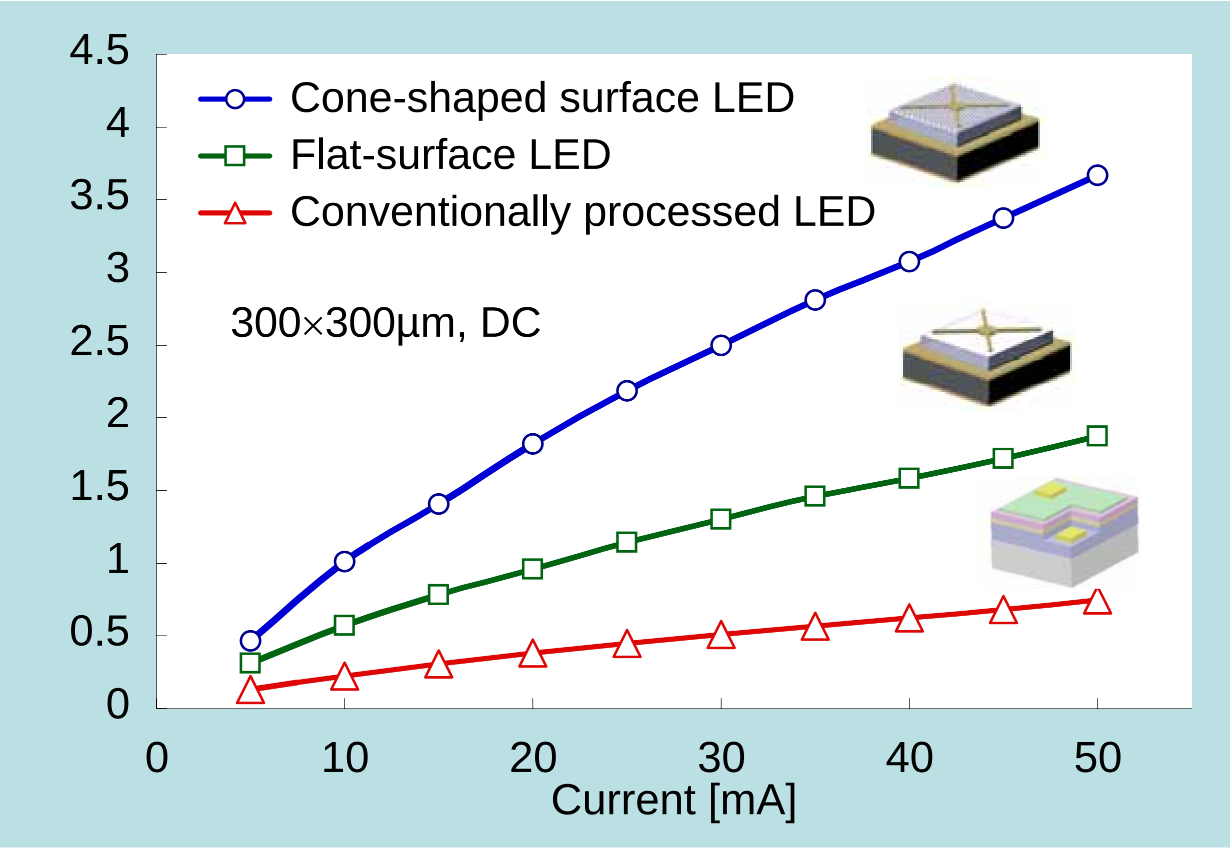
Enlarging the chip size



Lateral size of the µCone LED does not affect extraction

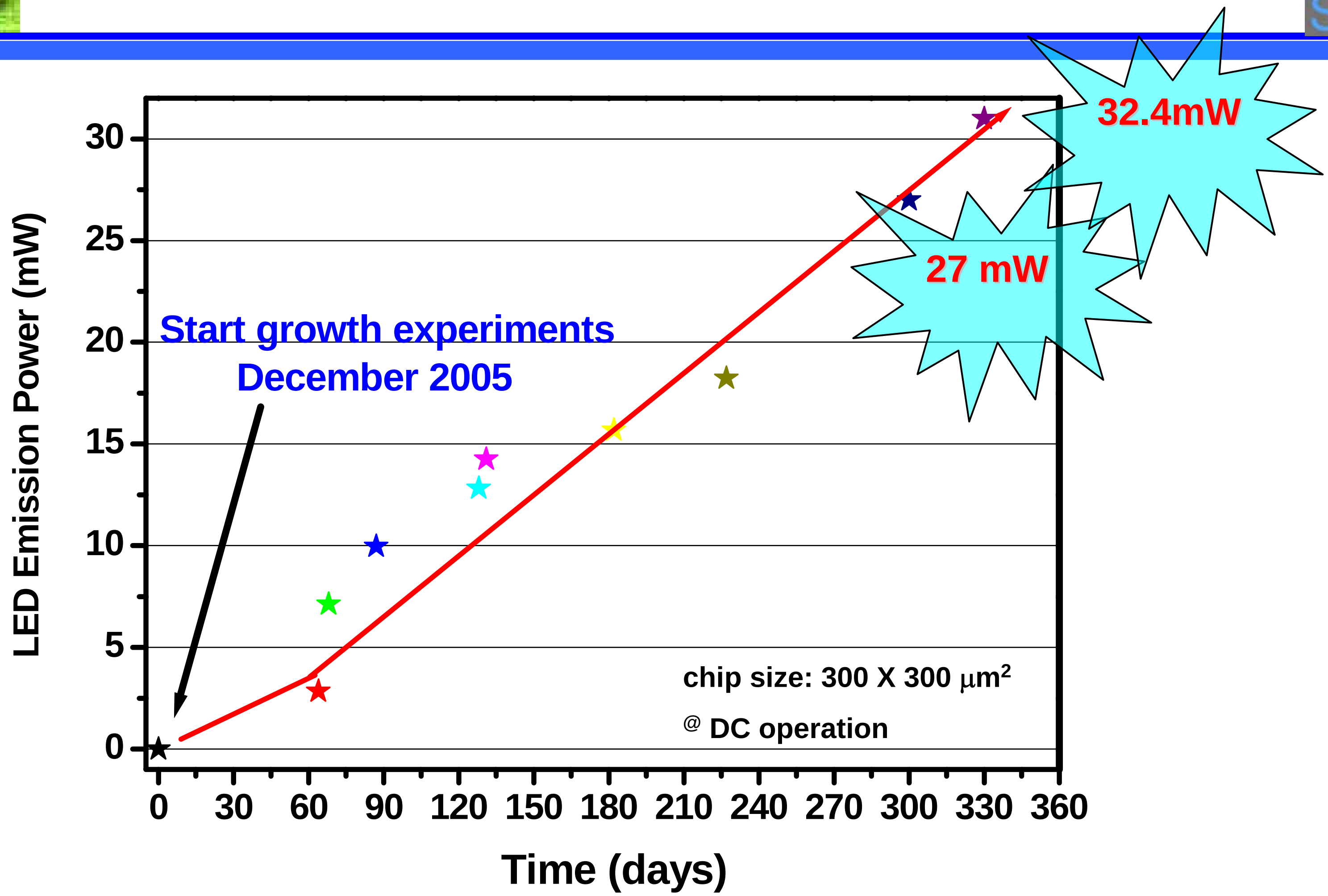
L-I characteristics





- **Upper light out put power from a cone-shaped surface LED is more <u>4 times greater</u> than a conventionally processed LED In unpackaged form.**

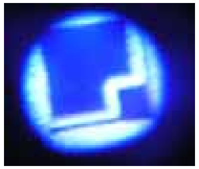
Tremendous Progress in C-Plane Polar LEDS

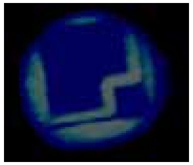


Achieved 32.4 mW @ 20mA

New Types of GaN Based LEDs for SSL

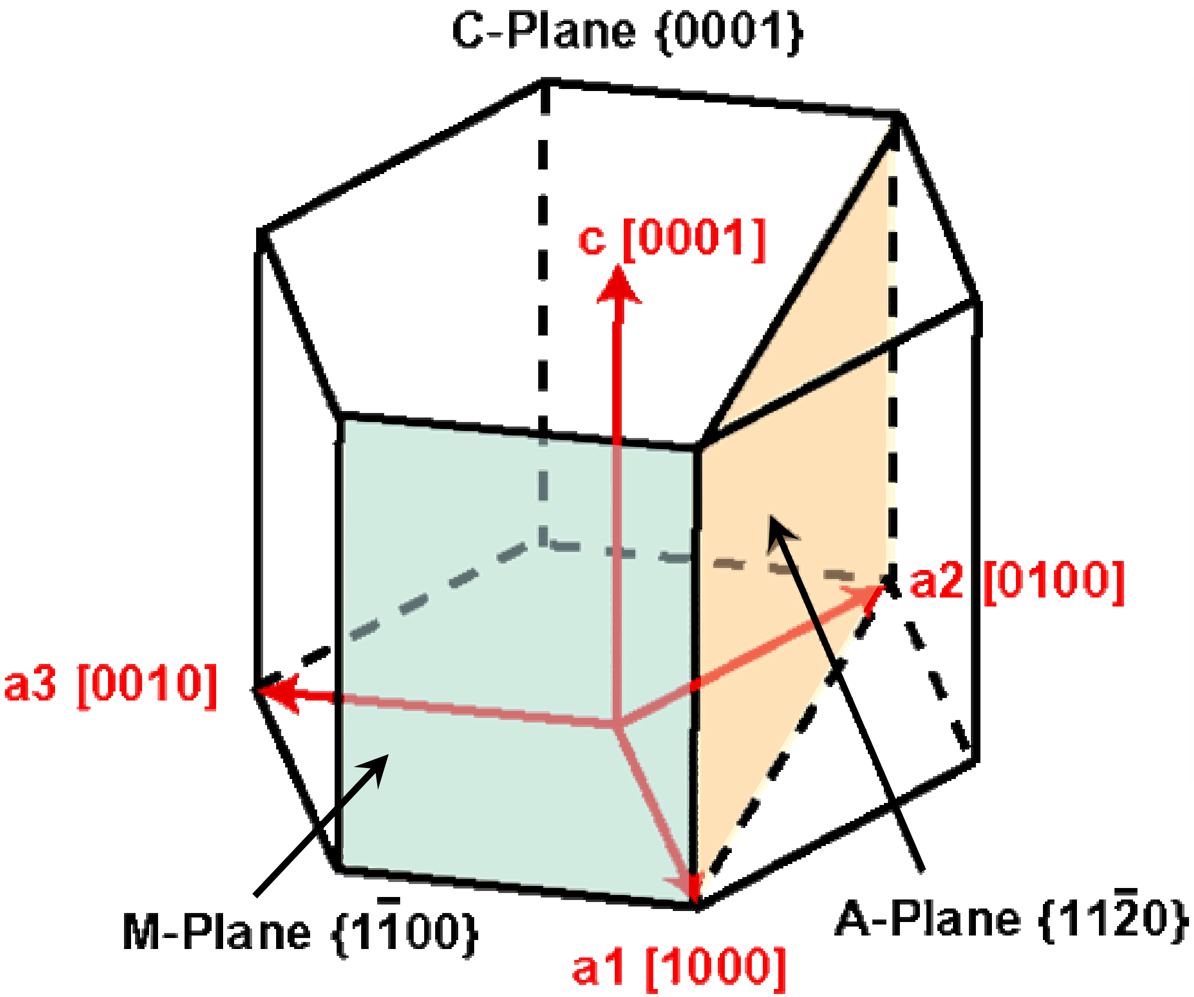
- **Nonpolar/Semipolar LEDs and LDs**



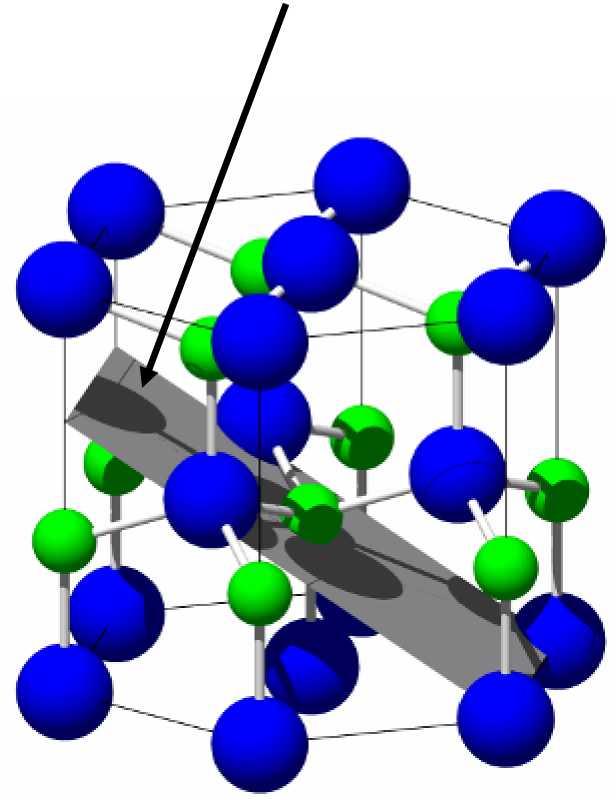


GaN Crystal Structure

Nonpolar GaN

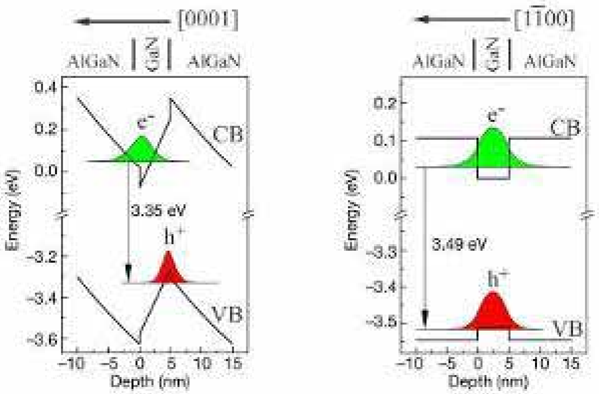


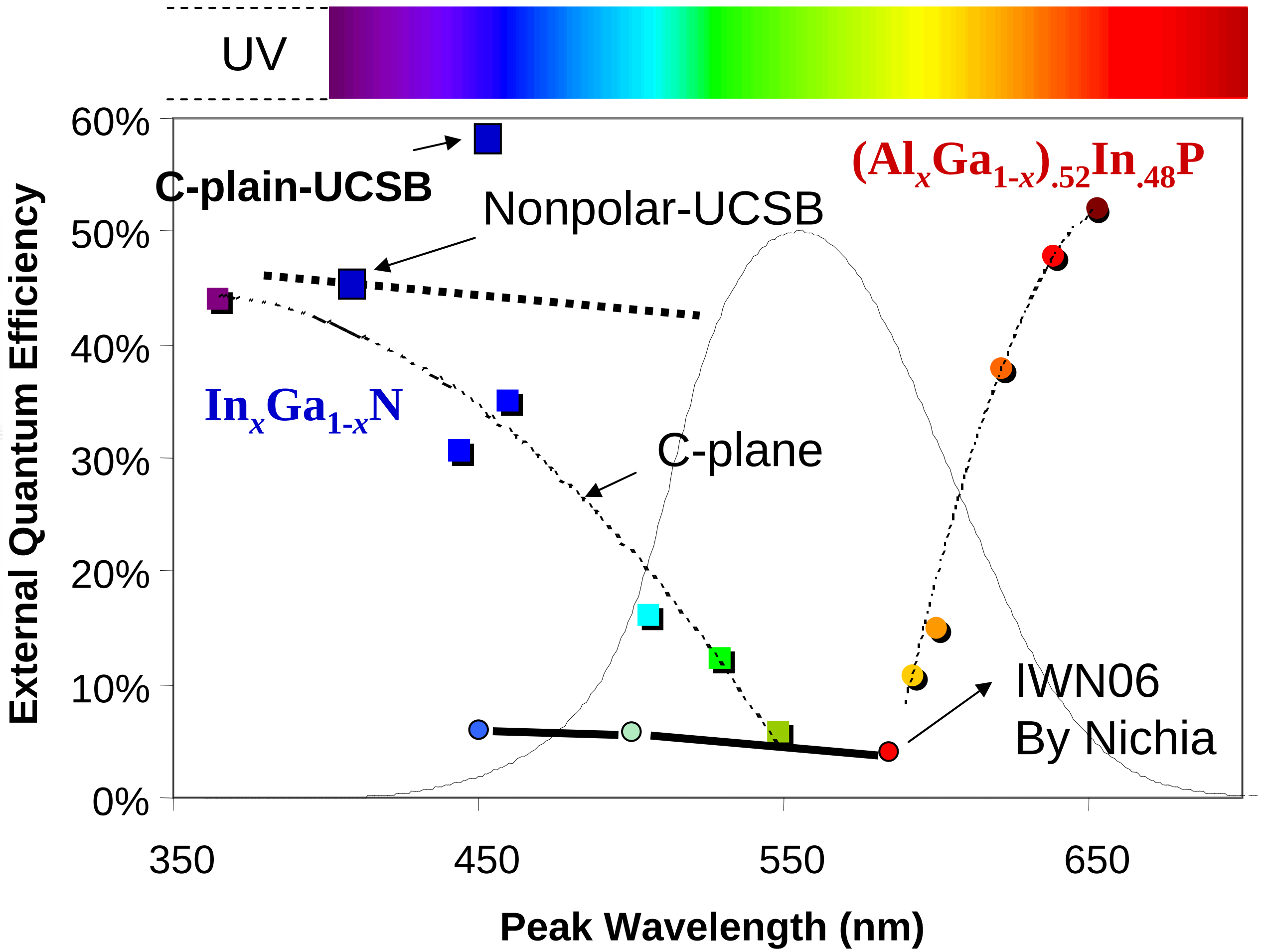
Semi polar GaN



Non-Polar GaN: LED Efficiency vs. Wavelength

- Polarization fields in polar QWs create problems in **green, ultraviolet, can Nonpolar solve the green gap?**

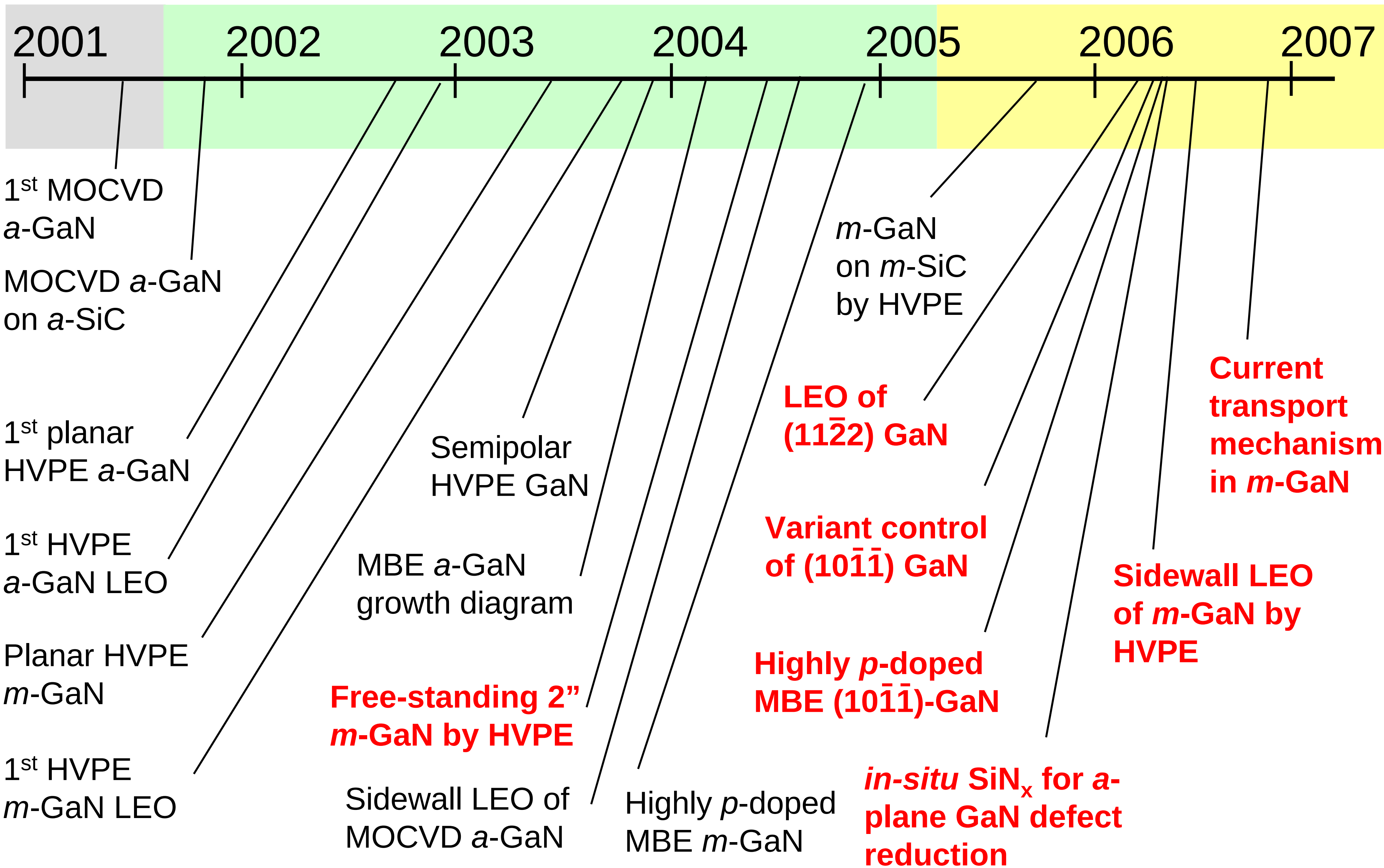




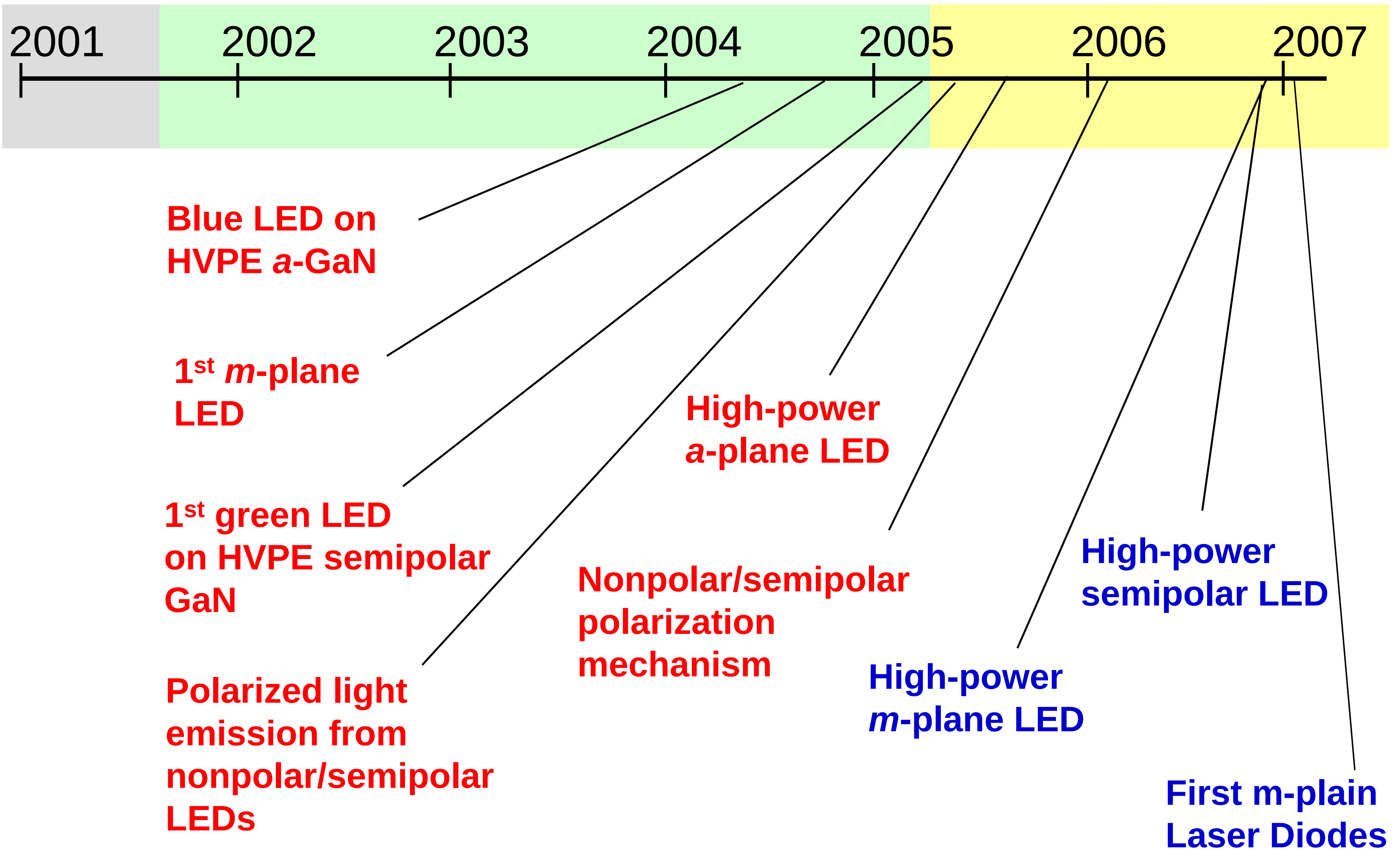
Goals of Nonpolar/Semipolar GaN

- ***Replacement of conventional c-plane GaN with Nonpolar/Semipolar GaN to create highly efficient LEDs and LDs.***

Research accomplishments – Nonpolar/semipolar Growth at UCSB

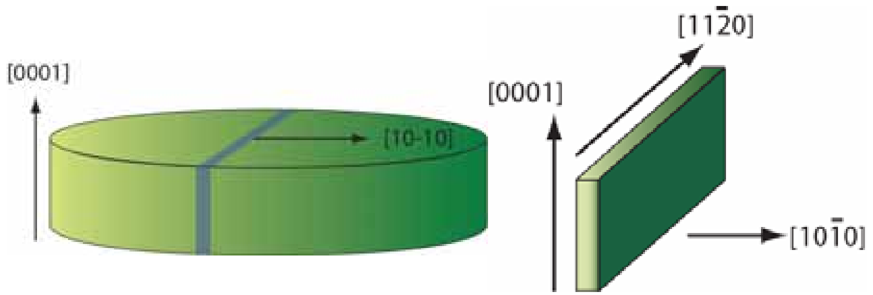


Research accomplishments – Nonpolar/semipolar devices at UCSB



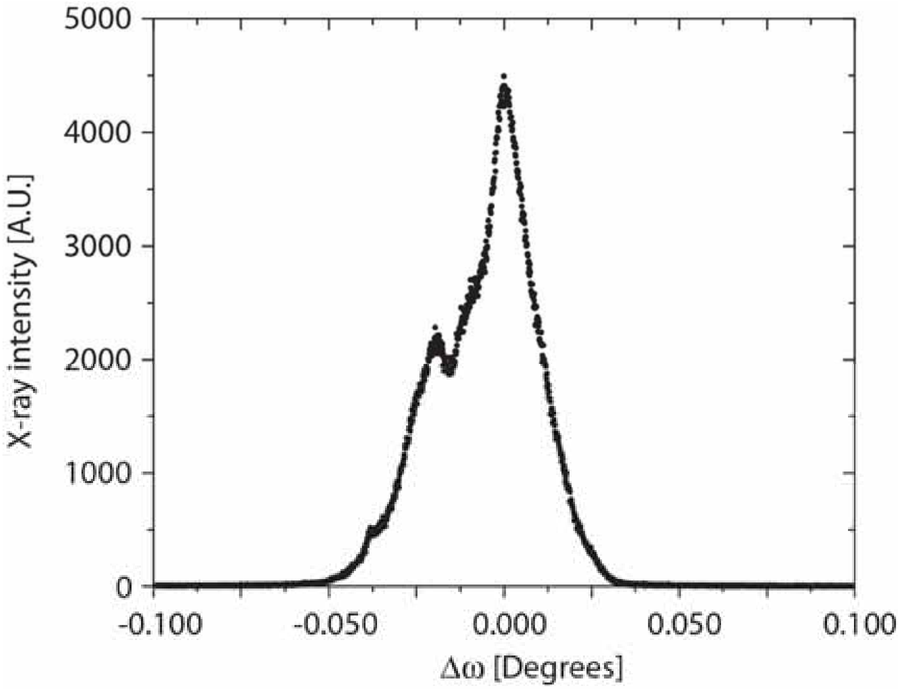
Latest Performance of Nonpola/Semipolar LEDs and LDs

Bulk GaN Substrates



m-GaN substrates cut from
c-plane HVPE grown GaN boules

XRD omega scan of (10$\underline{1}$0) parallel to [0001]

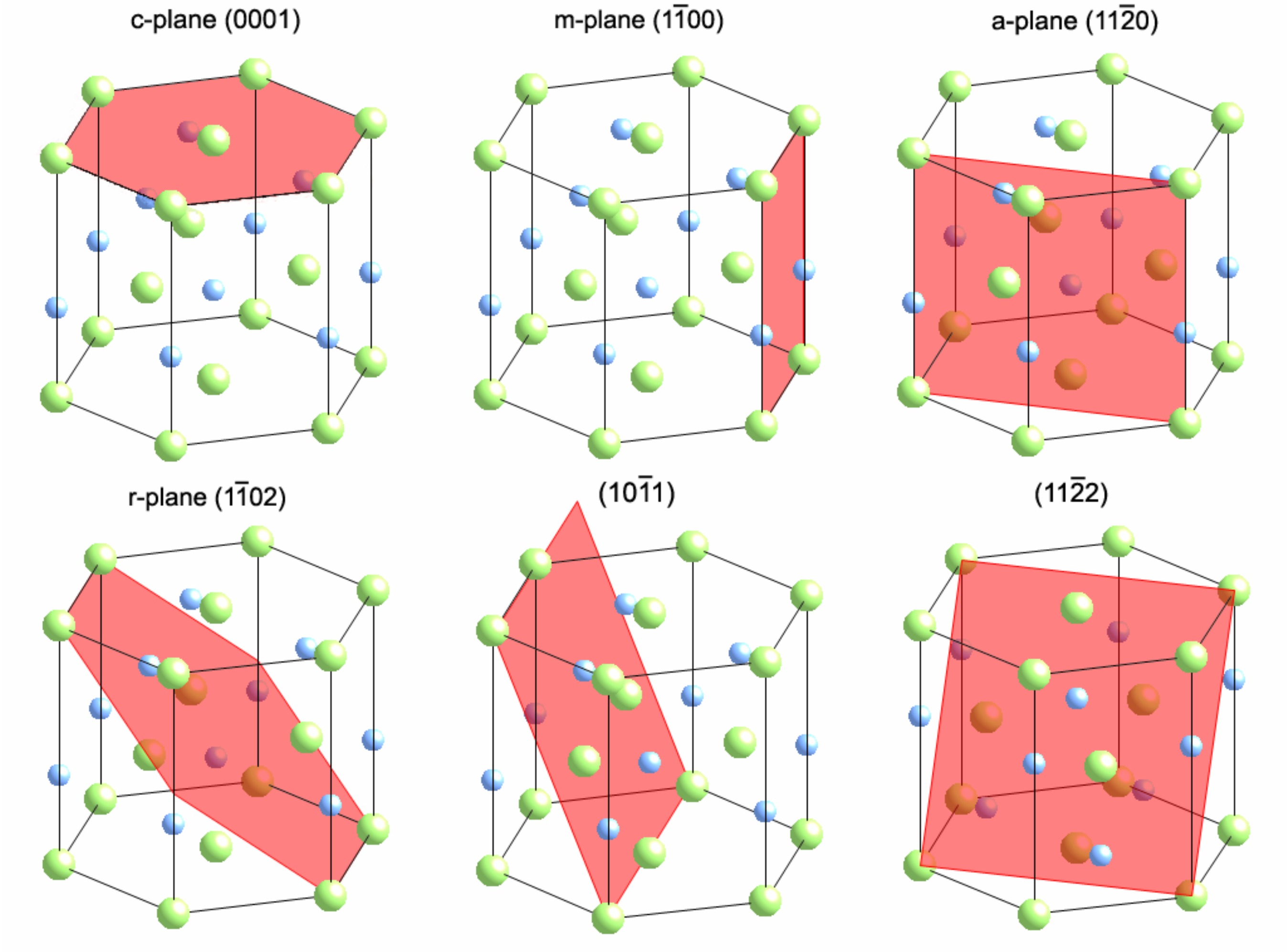


Bulk substrates grown and fabricated by Mitsubishi Chemical Corporation

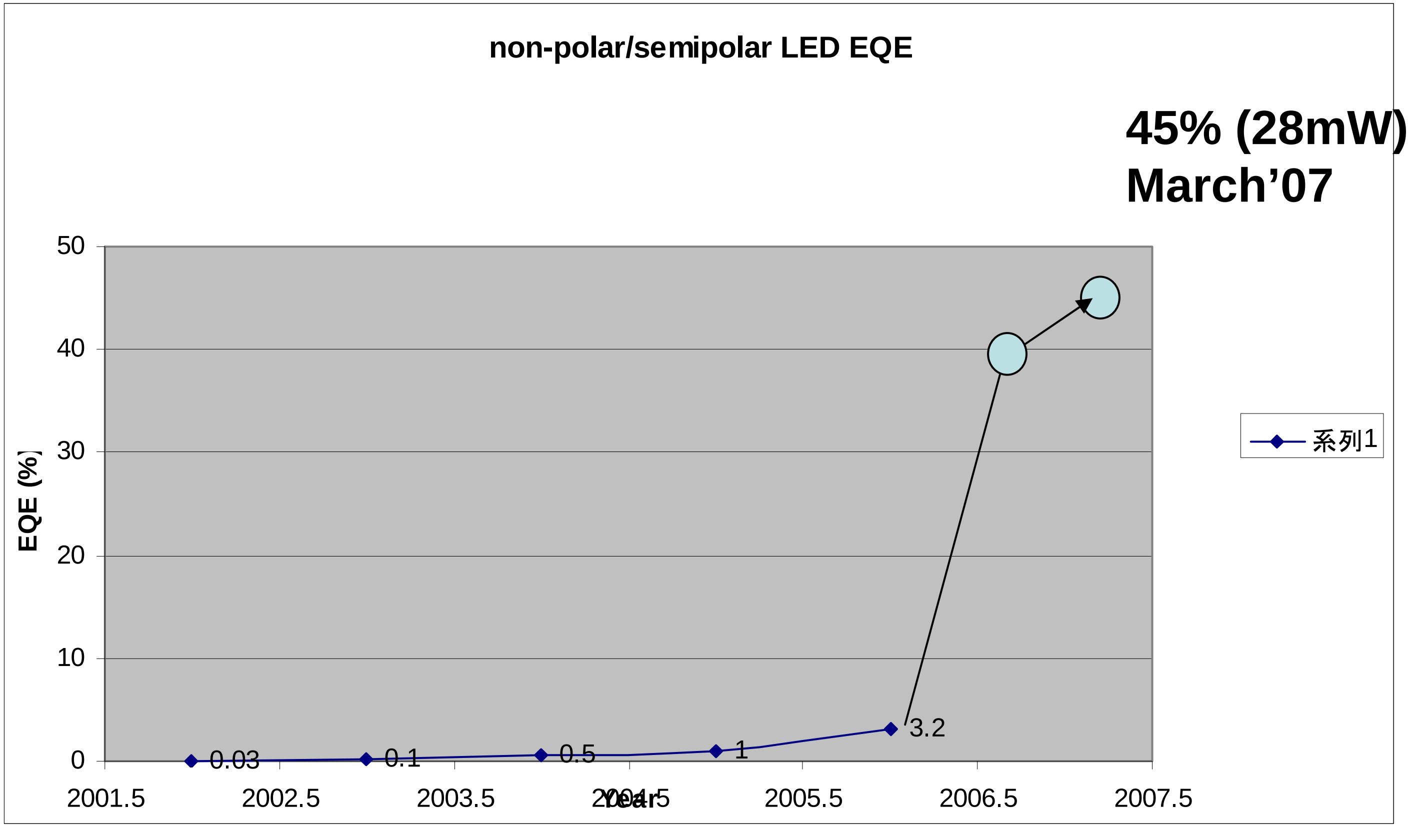
Multiple domains w/ FWHM ~0.02° (72 arcsec)

Extremely high quality

Wurtzite GaN Crystal Planes

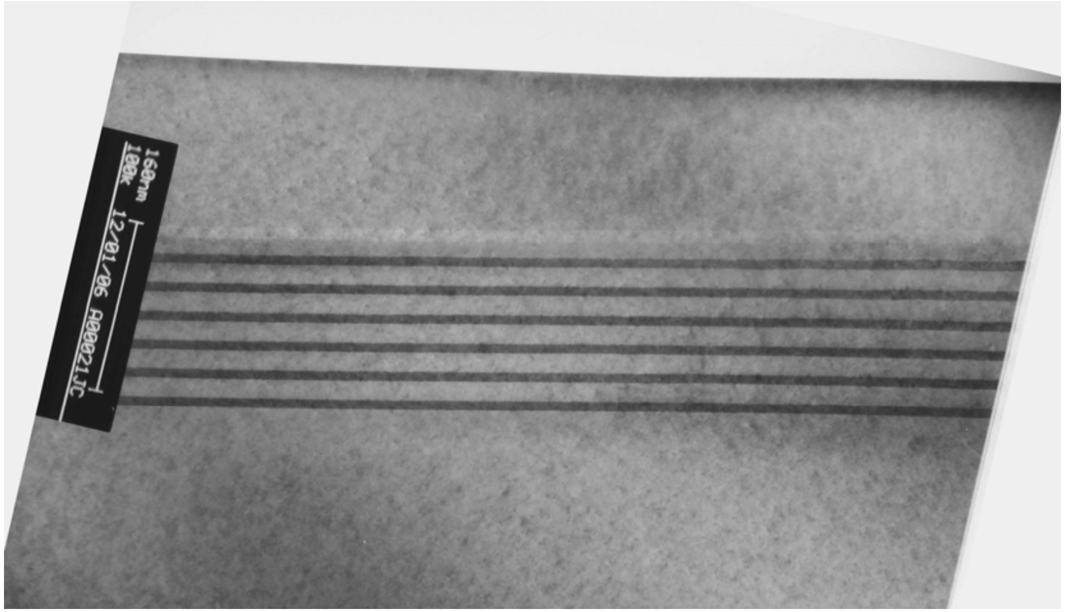


Breakthrough in Non-polar/Semi polar GaN LEDs



•All on Standard NiAu Chip/Package

Transmission Electron Microscope (TEM) Image of *m*-Plane LED

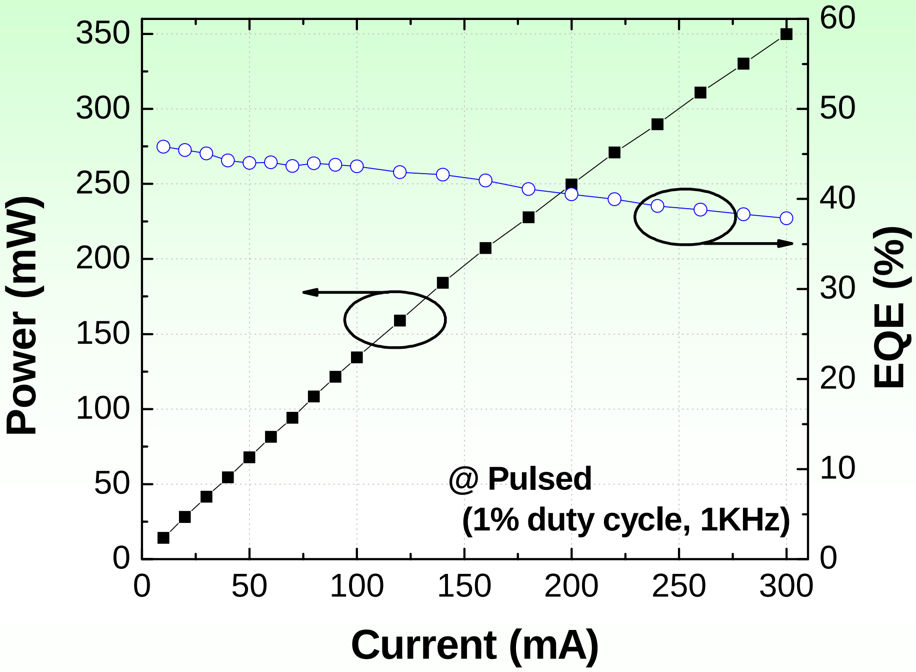


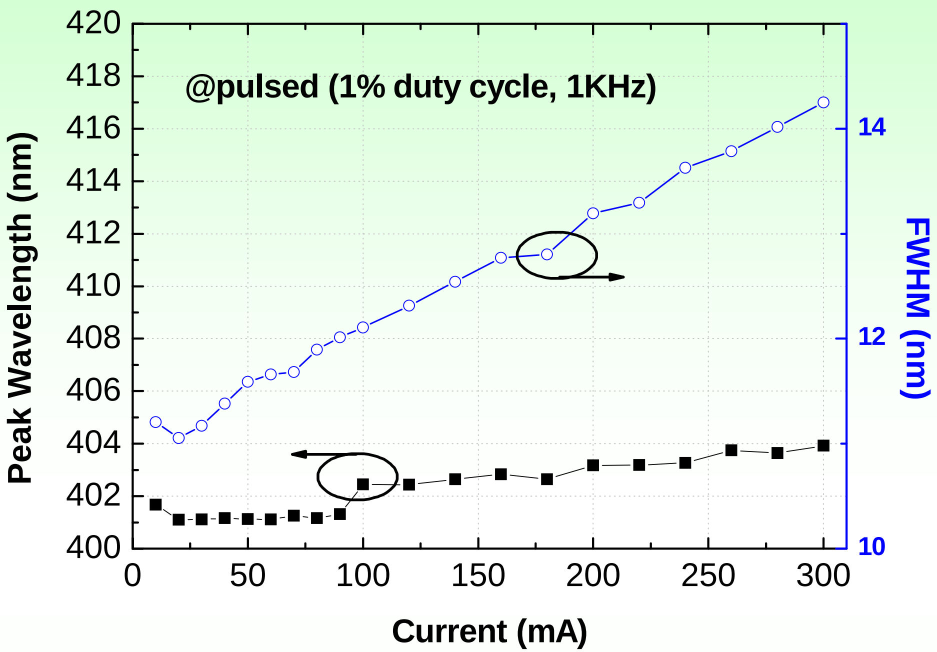
6x MQW 80 Å well / 180 Å barrier
AlGaN BL ~10 nm
p-GaN ~160nm

TEM courtesy of Dr. Feng Wu

- All growth rates appear to be very similar to *c*-plane
- No dislocations or stacking faults present

The LED at 400 nm

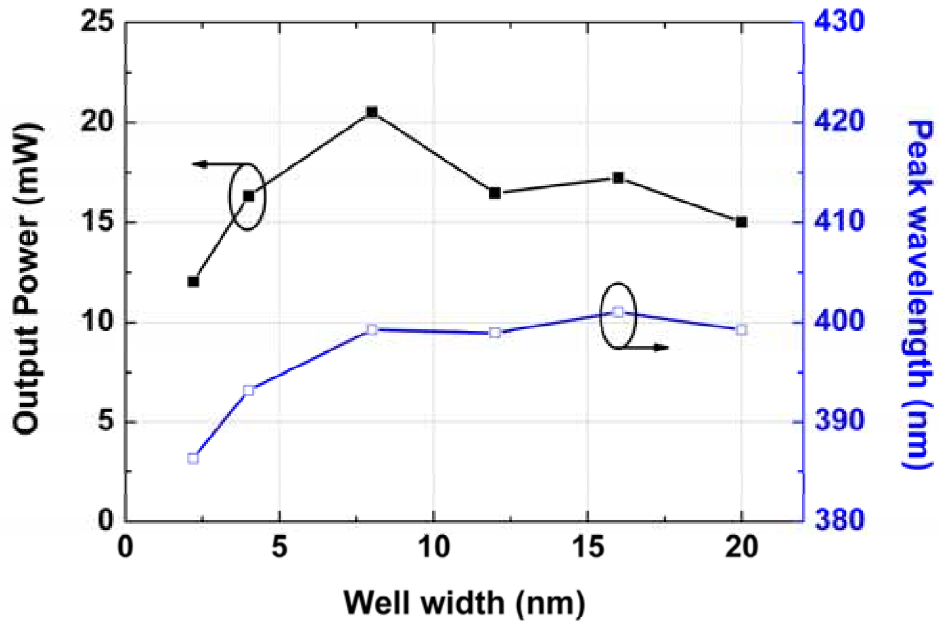




28 mW and 45.4% at a pulsed drive current of 20 mA
Flat EQE (46% at 10mA, 41% at 200mA)
250 mW and 41% at 200 mA
On this wavelength, WORLD RECORD over *c*-, and *m*-plane GaN LEDs

Dependence of LED Performance on Well Width

- 6x MQW well width series
- Standard fabrication w/ ITO p-contacts
- Standard packaging technique w/ epoxy dome



- Up to 20 nm quantum wells worked well
  - Essentially a double heterostructure
- Maximum power emission with 8-10 nm wells
- Wells thicker than ~4 nm do not work well if at all in *c*-plane devices due to polarization fields
- Huge implications for laser diode design…

Semipolar Blue/Green LEDs

Semipolar GaN Advantages

- Similar advantages to nonpolar
  - Reduced polarization related fields
  - Higher gain expected
  - Reduced blue shift

Possible additional advantages over nonpolar

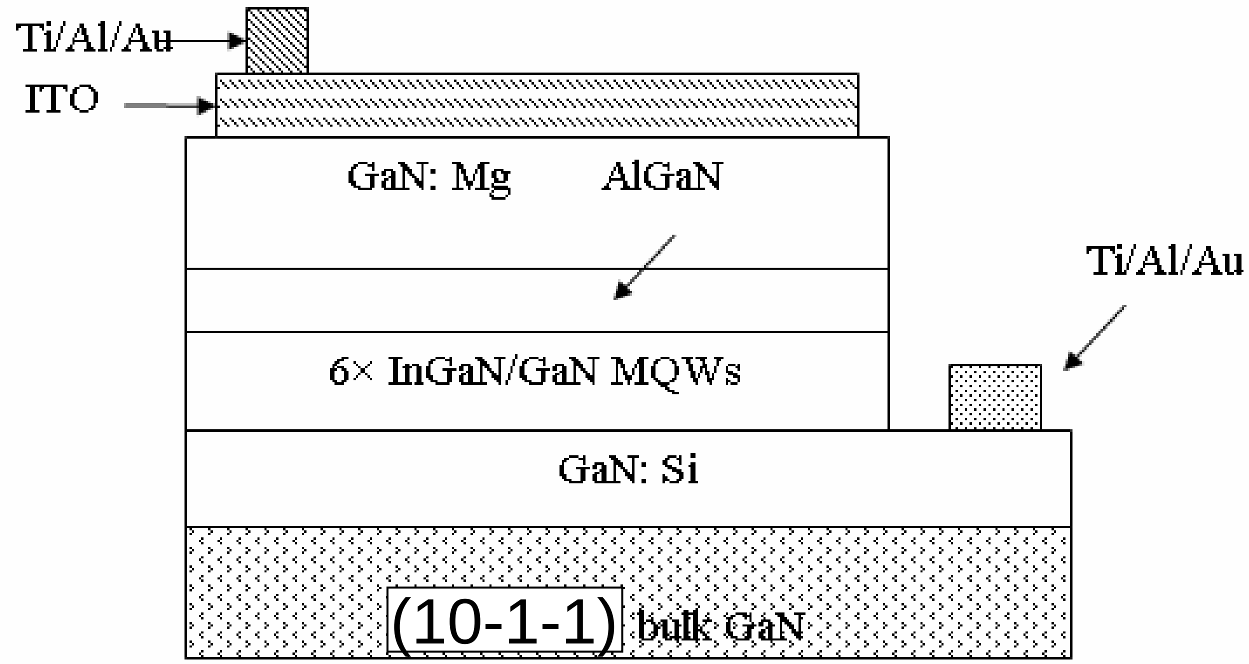
- A wide variety of feasible orientations, including {10-1-1}, {10-1-2}, {10-1-3} and {11-22}
- Better performance at longer wavelengths (500nm)
  - Higher In incorporation (?)

UCSB – Semipolar GaN Milestones

- First Demonstration of…
  - Planar semipolar GaN templates [a)]
  - Semipolar LEDs on planar {10-1-1}, {10-1-3} GaN films [b)]
  - High Mg incorporation in {10-1-1} GaN films [c)]
  - High performance LEDs [d)]
  - Semipolar LD [e)]

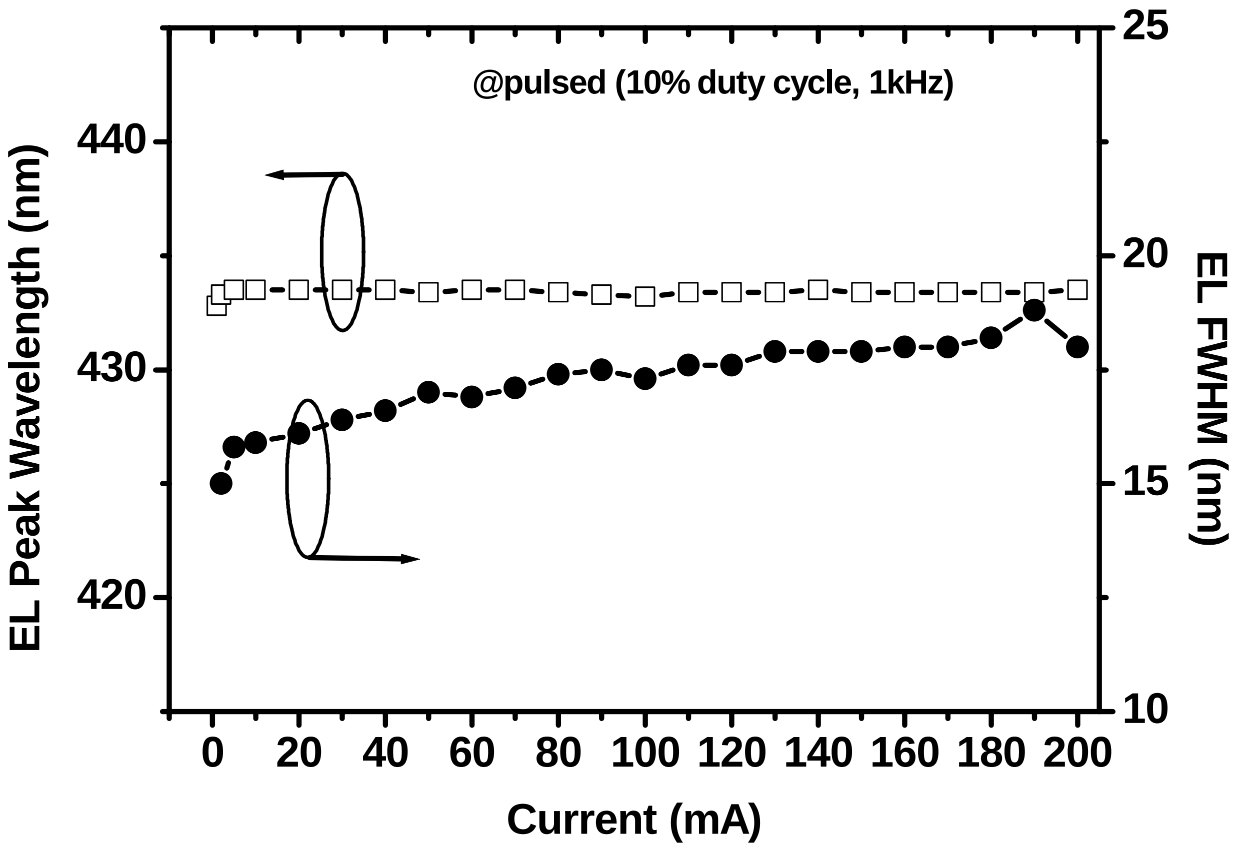
a) Baker *et al., Jpn. J. Appl. Phys.*, **44** (2005)
b) Chakraborty *et al., Jpn. J. Appl. Phys.*, **44** (2005)
c) Kaeding *et al., Appl. Phys. Lett.*, **89** (2006)
d) Tyagi *et al.,Jpn. J. Appl. Phys.*, **46** (2007)
e) Tyagi *et al.,Jpn. J. Appl. Phys.*, **46** (2007)

Semipolar Blue LED



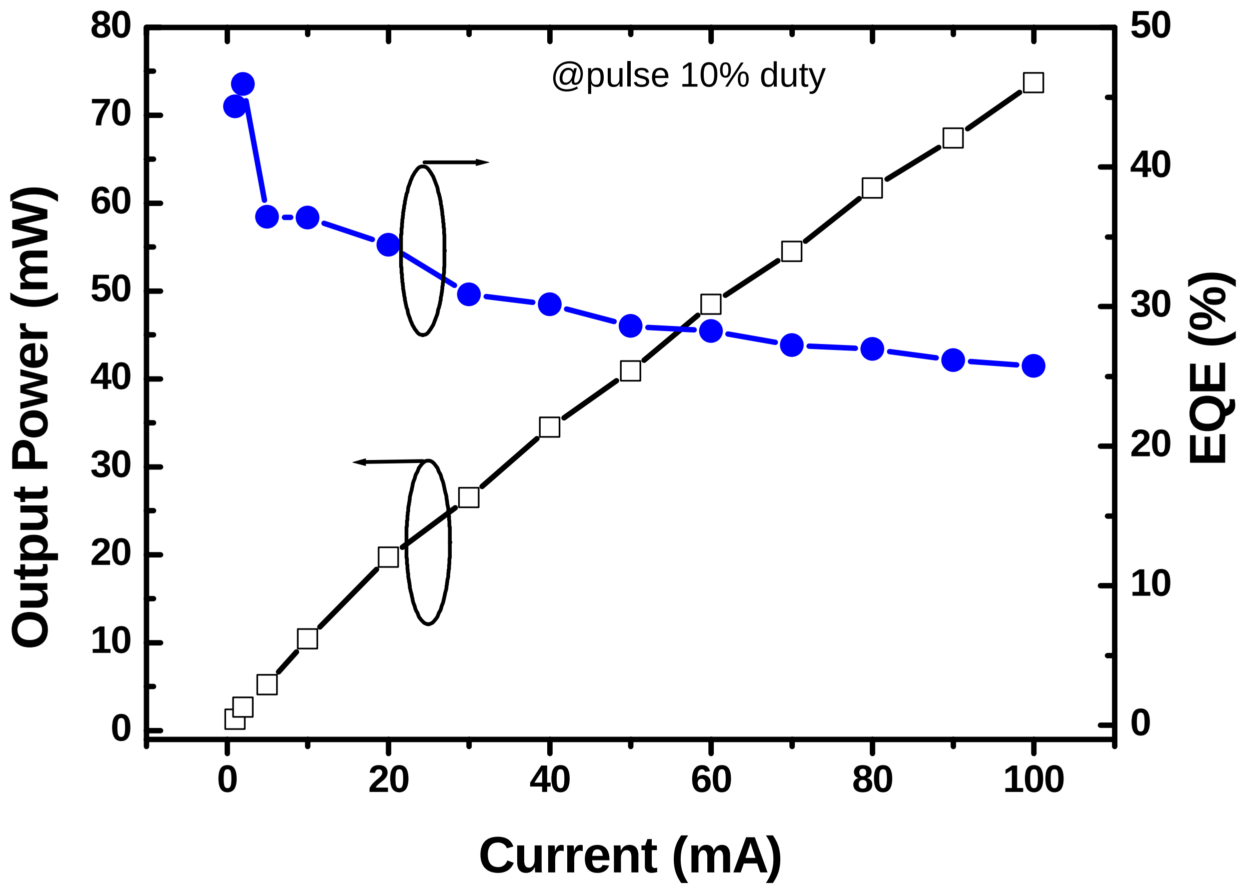
LED structure on (10-1-1) bulk GaN

Blue (10-1-1) LED- current vs peak wavelength, width



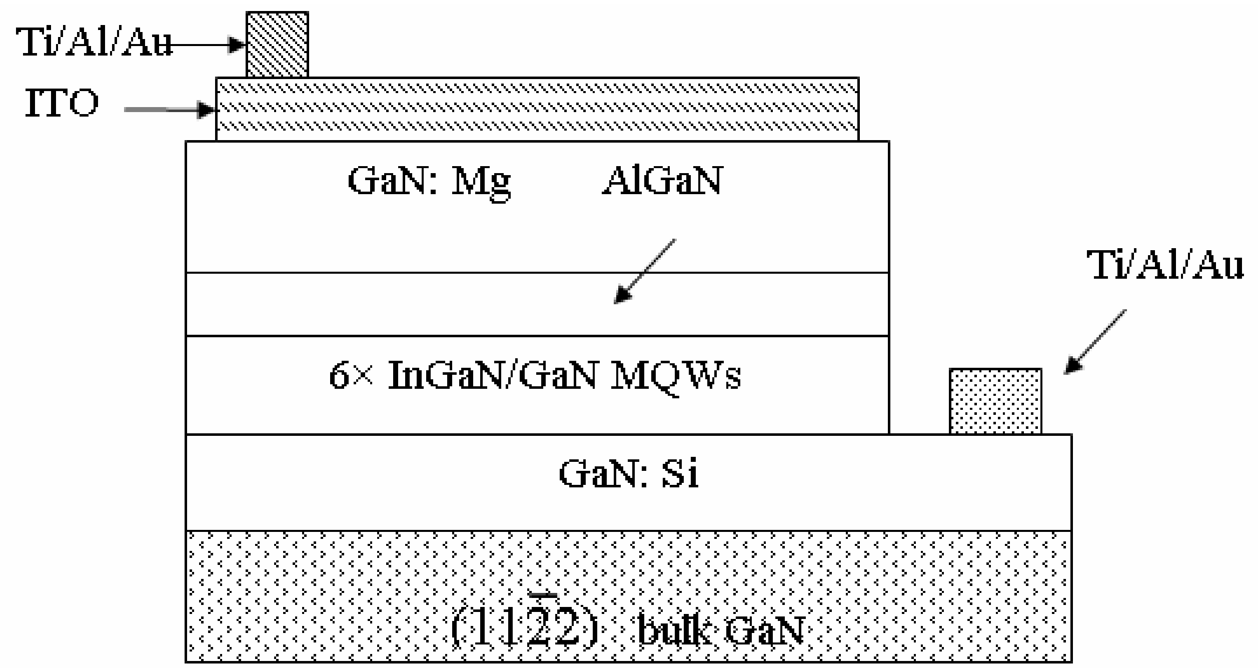
Blue shift : -0.7 nm over 200 mA range (1 - 200 mA)

Blue (10-1-1) LED- Output power and EQE with DC current



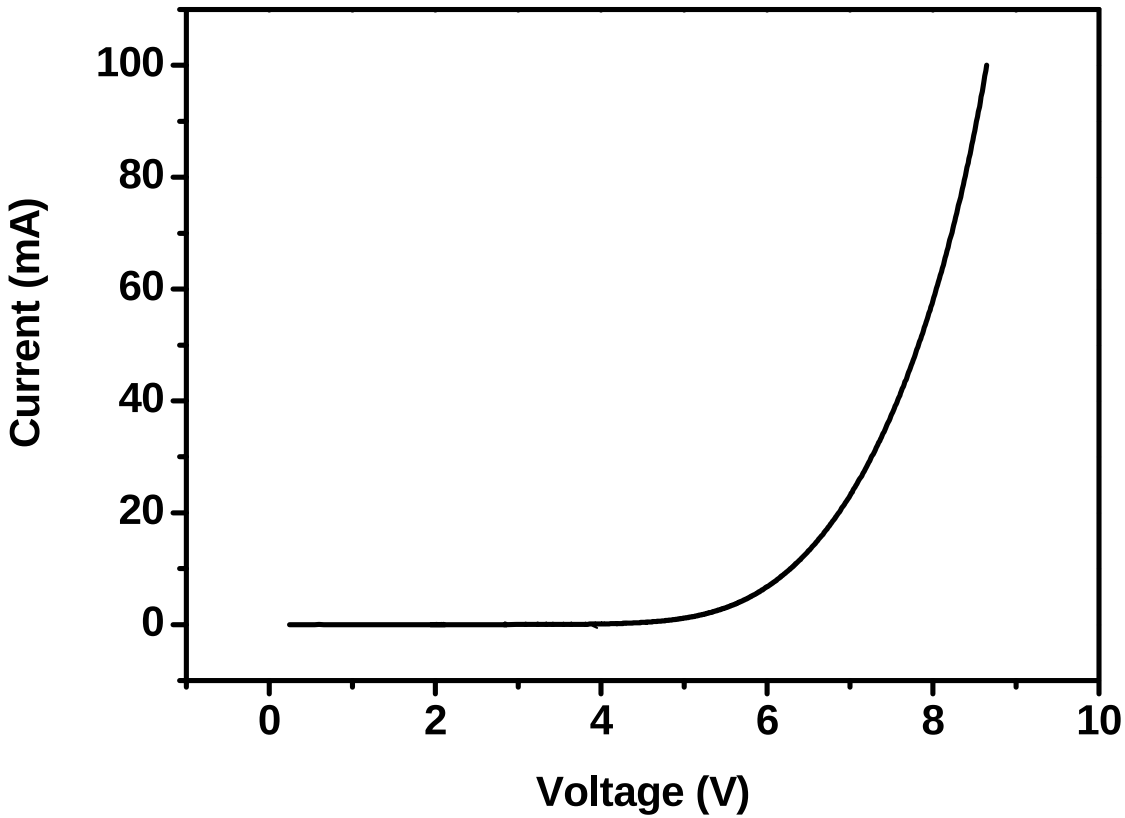
19.7 mW @ 20 mA (34.4% EQE), 73.7 mW @ 100 mA (25.7% EQE)

Green LED



LED structure on (11-22) bulk GaN

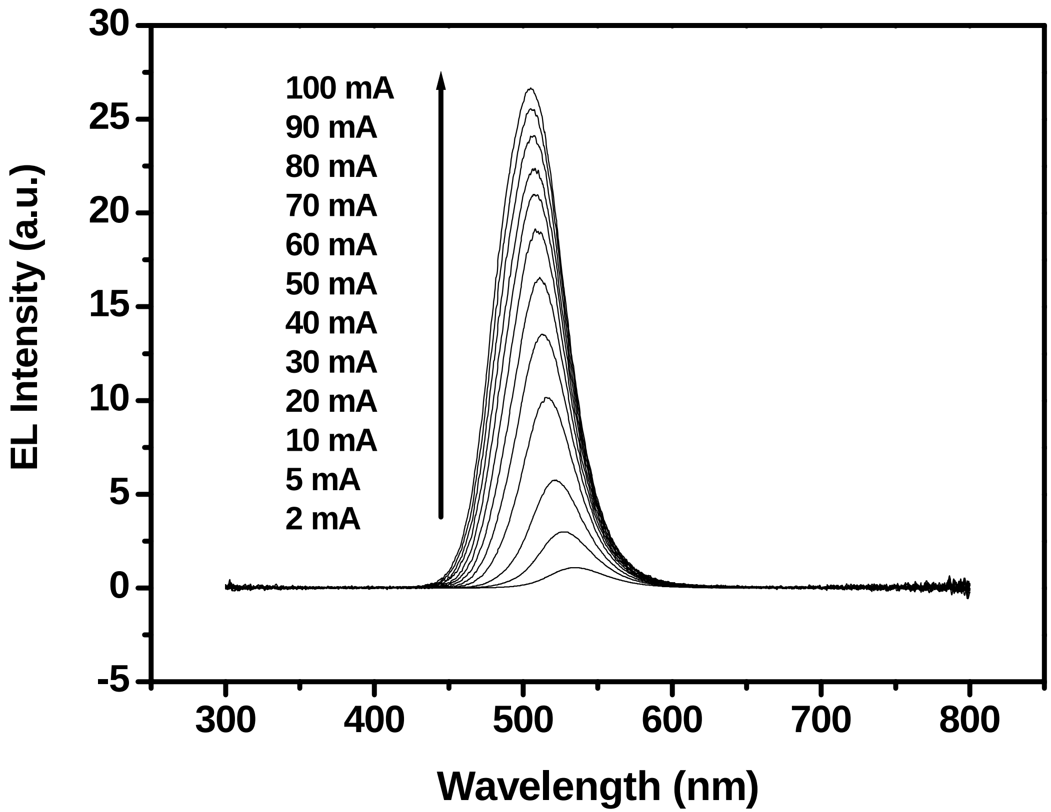
Green LED- I-V characteristics



·**Driving voltage : 6.9 V at 20 mA**

unoptimized growth conditions of the *p*-GaN layer and the ITO contacts

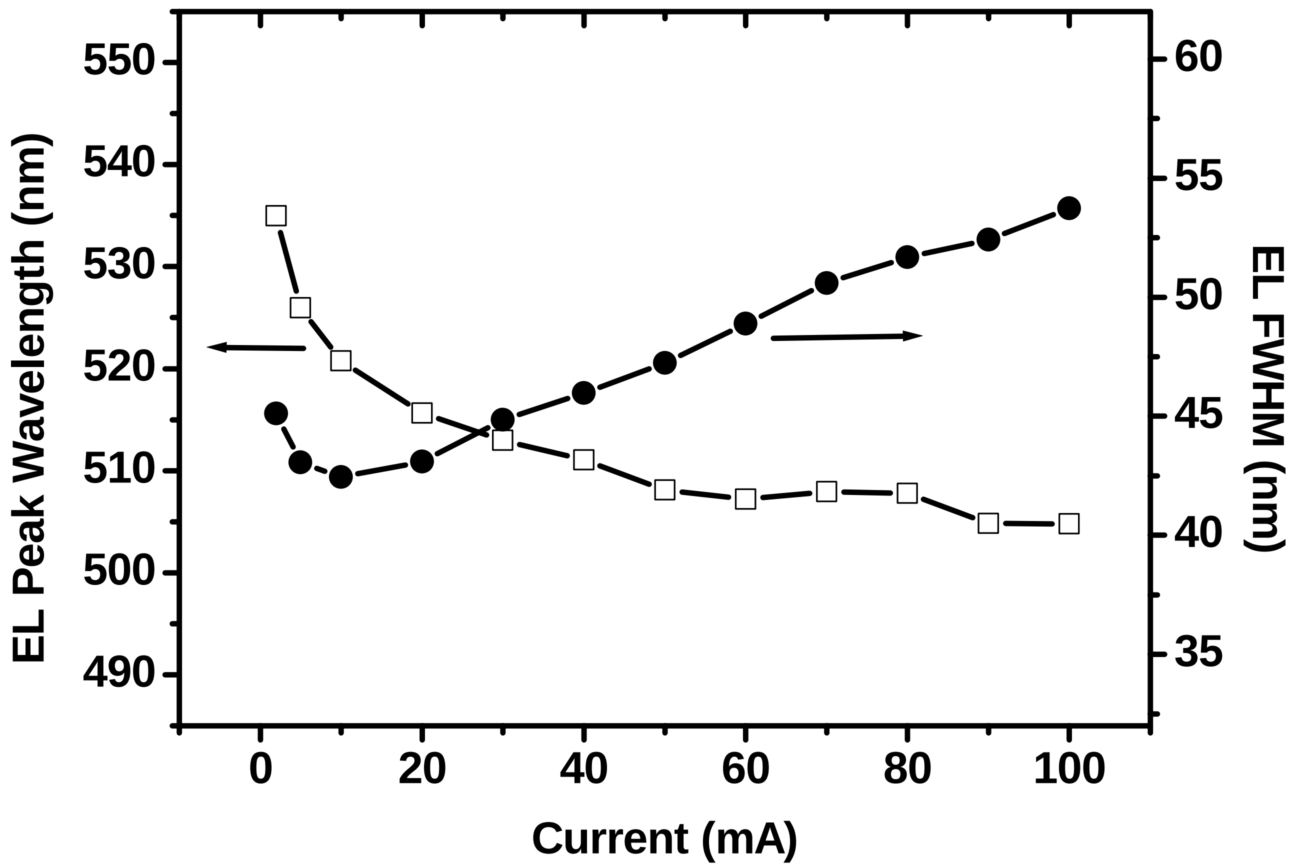
Green LED- EL spectra under DC



Peak wavelength : 516 nm @ 20 mA

FWHM : 43 nm @ 20mA

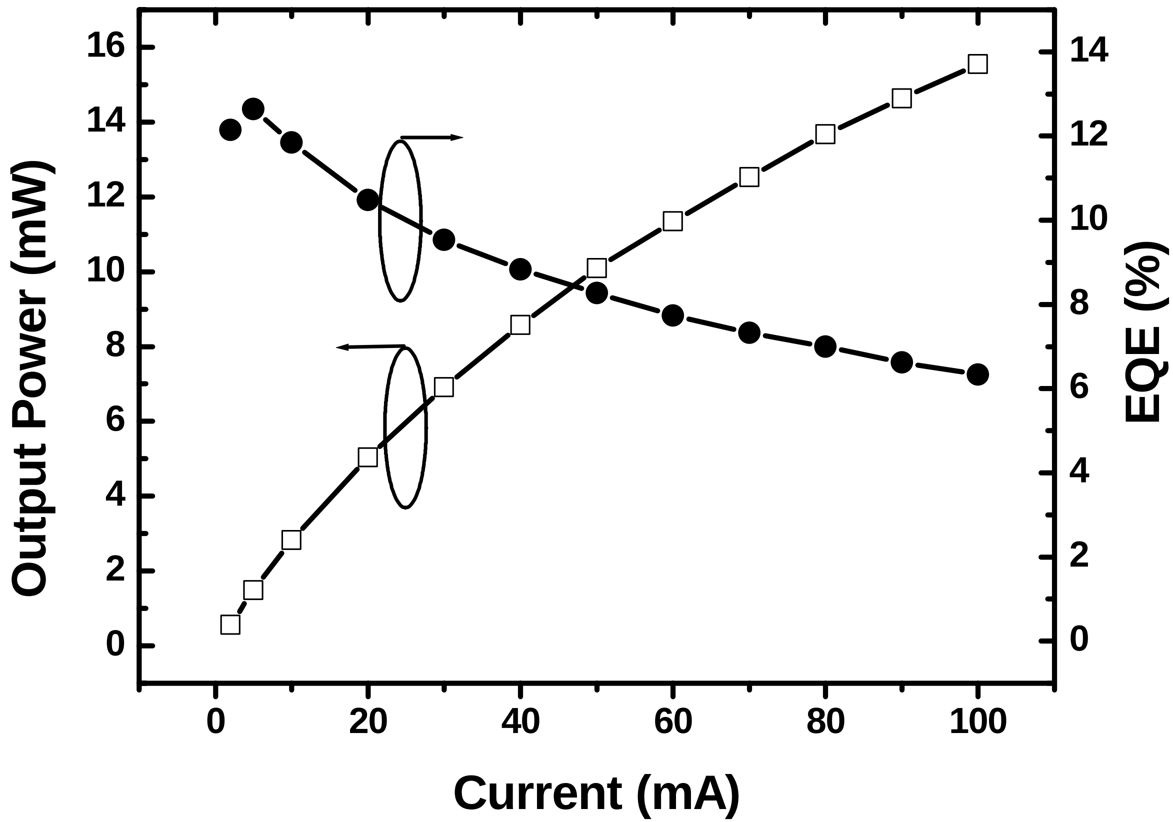
Green LED- current vs peak wavelength and width



Blue shift : 8 nm over 70 mA range (30 - 100 mA)

reduced polarization-related electric fields

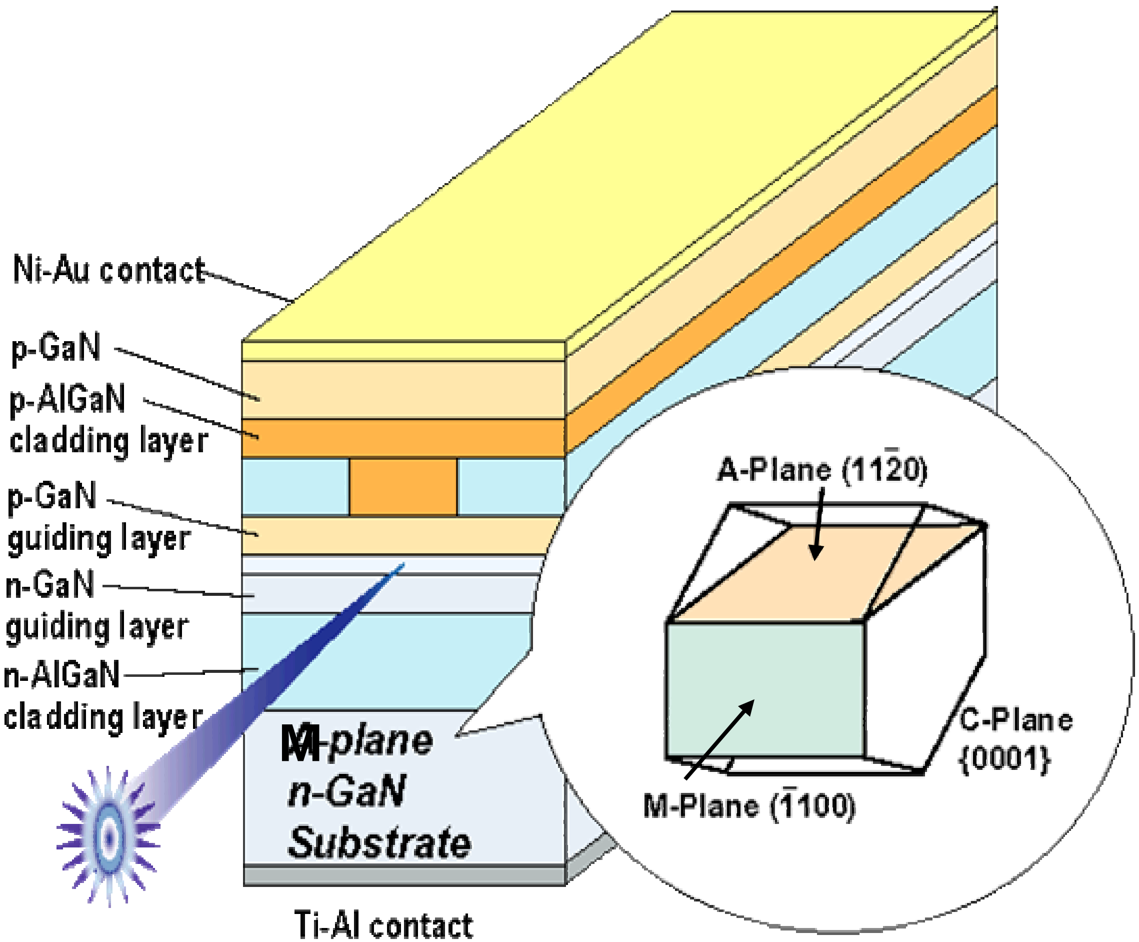
Green LED- Output power and EQE with DC current



5.0 mW @ 20 mA (10.5% EQE), 15.6 mW @ 100 mA (6.3% EQE)

Highest power ever reported on nonpolar/semipolar planes

Nonpolar/Semipolar GaN Motivation for LDs

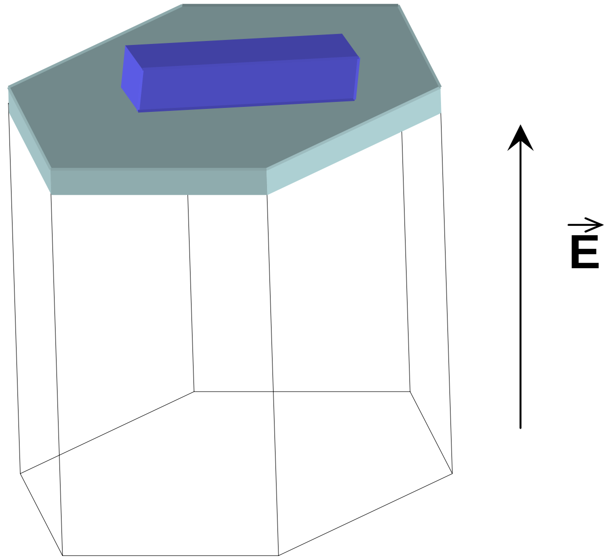


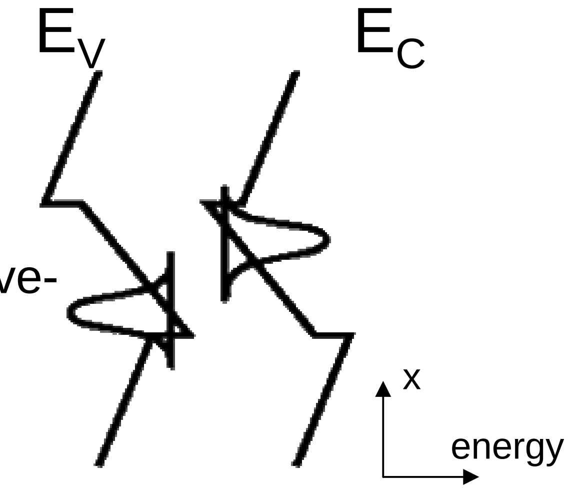
- Low dislocation density
- No polarization field-induced charge separation in QWs
- Lighter hole mass due to an uniaxial compressive strain
- Emission light is polarized along a-axis

- Large m-plain gain: 3-10 x c-plain gain

Low threshold current, High reliability

Conventional *c*-Plane (polar)

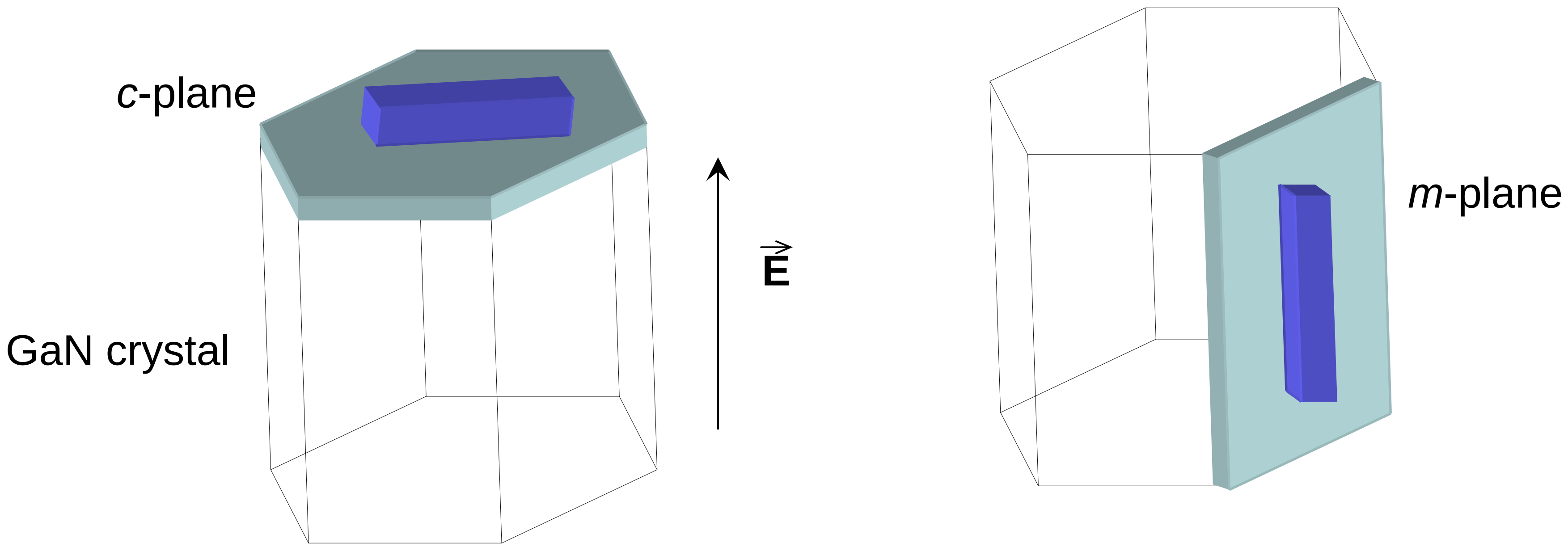




energy band diagram

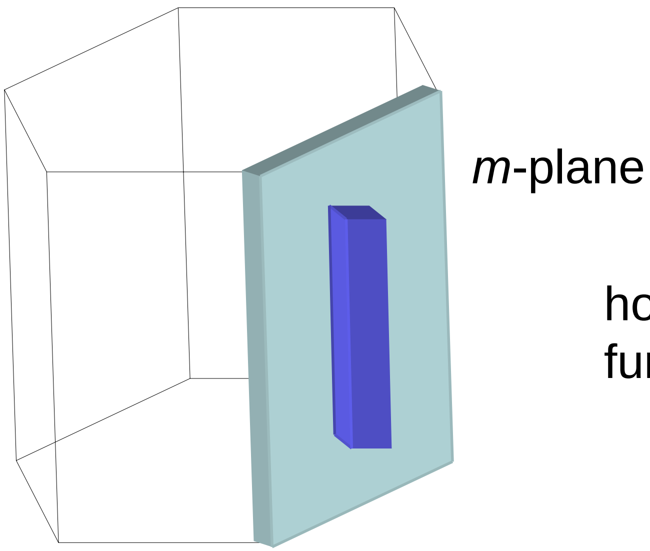
- There are unequal #'s of Ga and N atoms on the c-plane
- Charge offset causes an electric field along the c-axis (polar)
  - Quantum Confined Stark Effect (QCSE) leads to blue-shift at increasing drive currents (peak emission wavelength changes with current)
- Decreases electron and hole wave-function overlap
  - Decreases electron-hole recombination rate

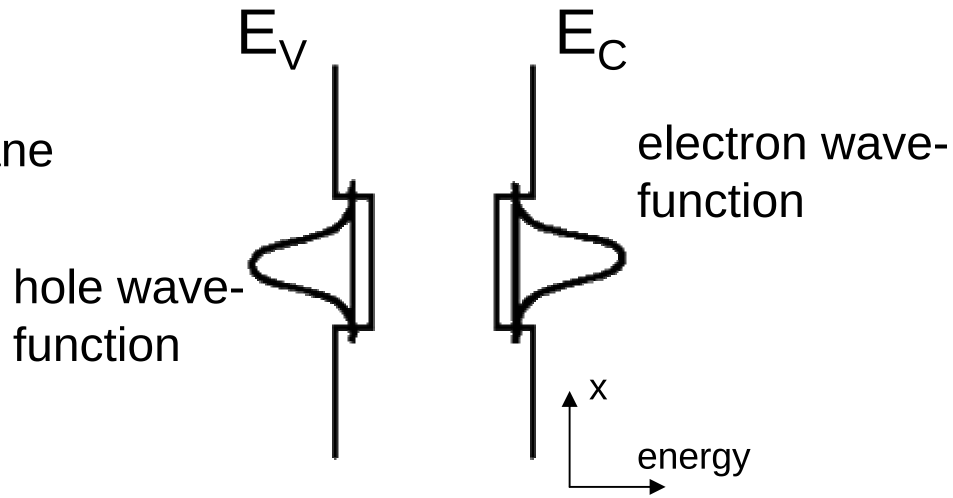
c-Plane (polar) vs. *m*-Plane (nonpolar)



- Fabricate lasers on the *m*-plane
- Past attempts have been unsuccessful due to inadequate substrates
- Accomplished by using a newly developed bulk GaN *m*-plane substrates

m-Plane (nonpolar)



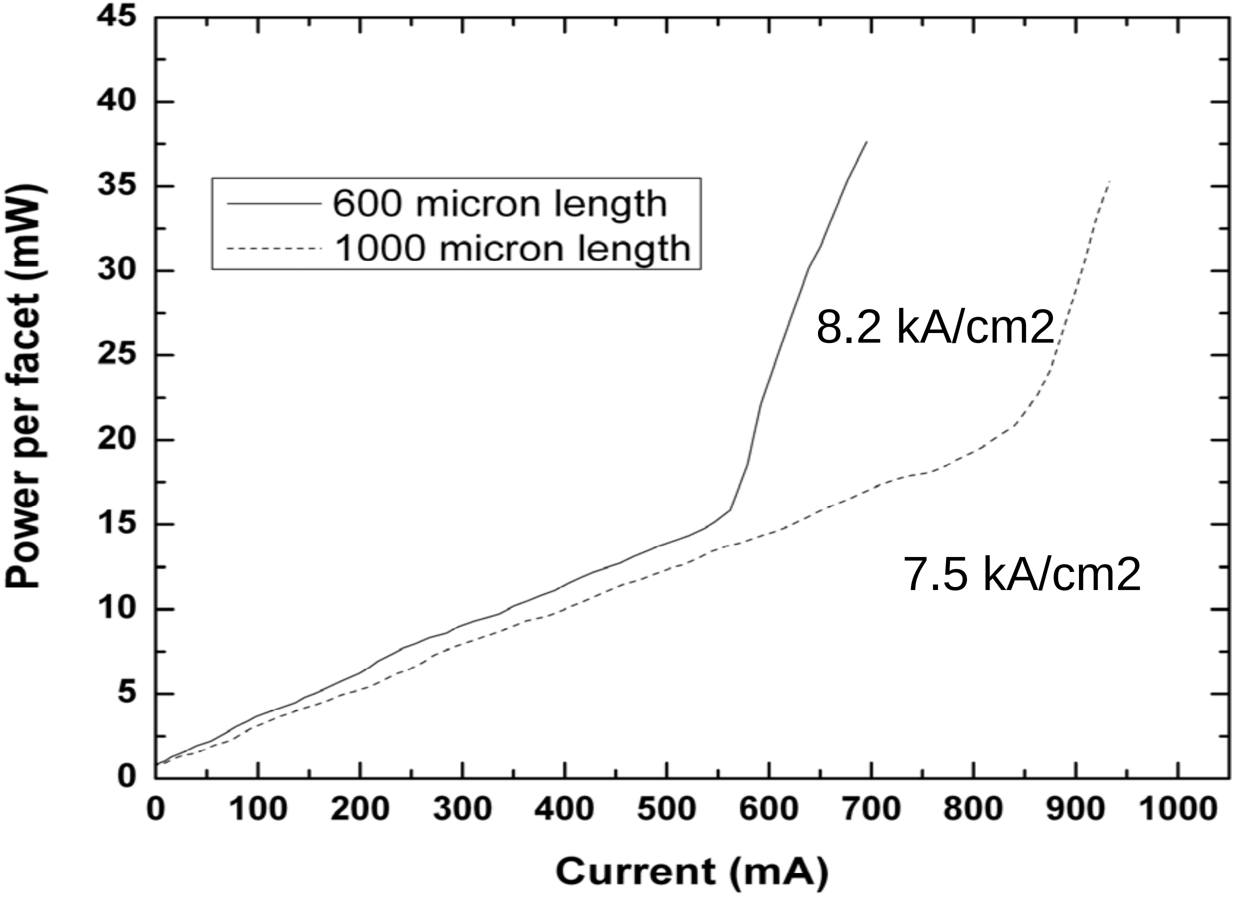


- *m*-plane contains the same # of Ga and N atoms
- No built-in electric fields
  - Peak wavelength does not change with drive current (no blue-shift)
- No spatial separation of electrons and holes
  - High recombination rate
- Higher gain
  - Reduced effective hole mass

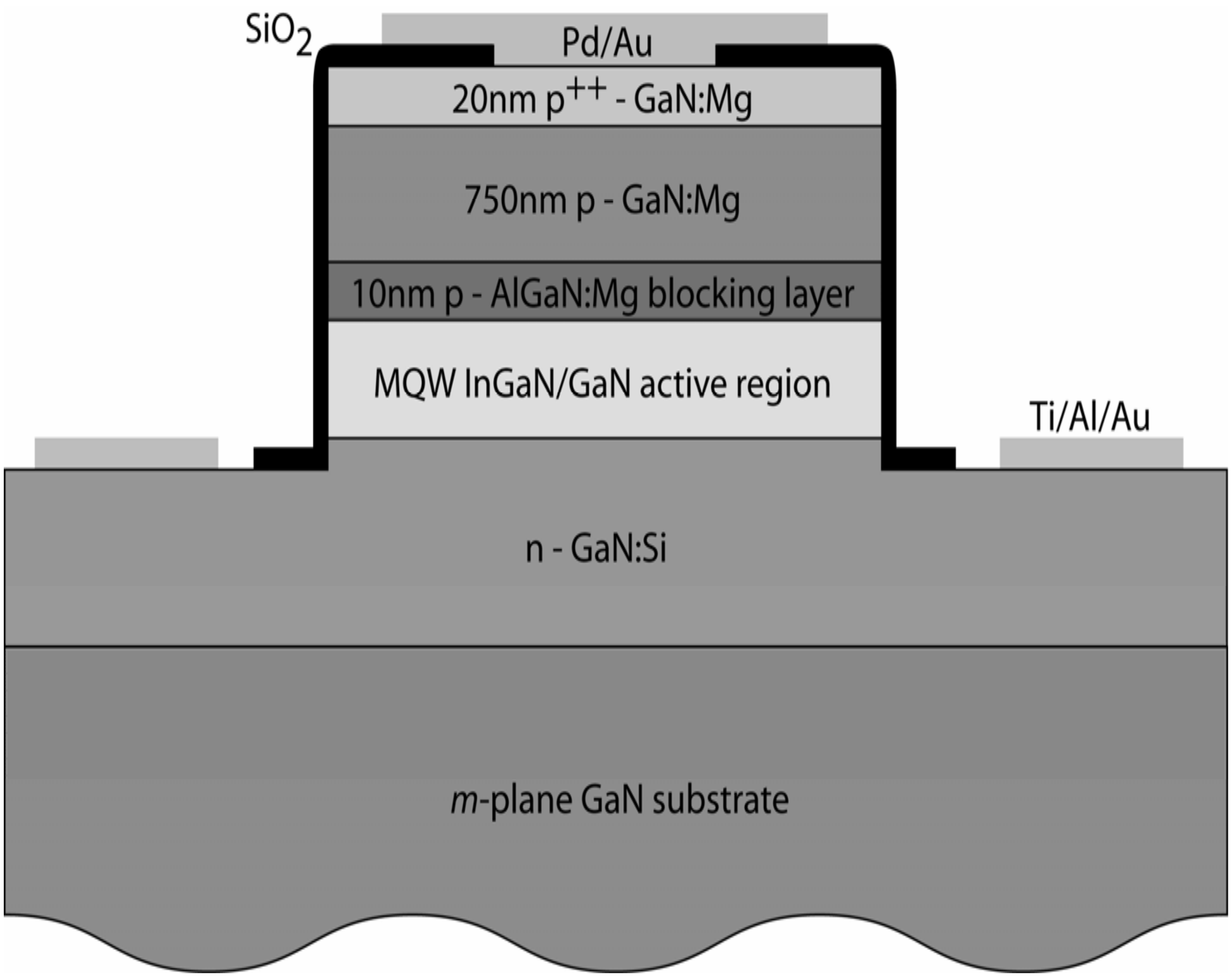
Broad Area Nonpolar (m-plain) Laser Diode

Stripe width 10 micron

January, 2007

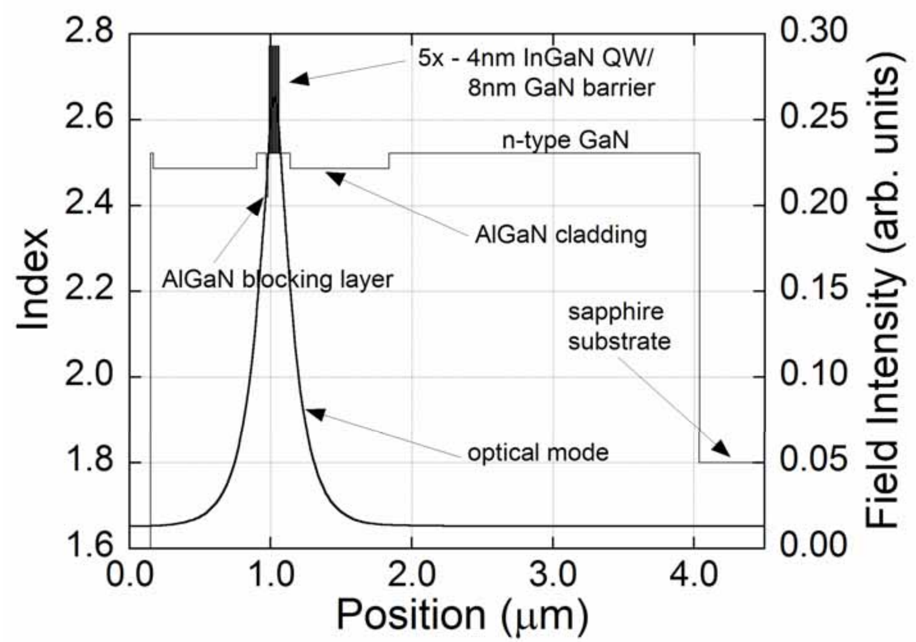


AlGaN-Cladding-Free Nonpolar LD



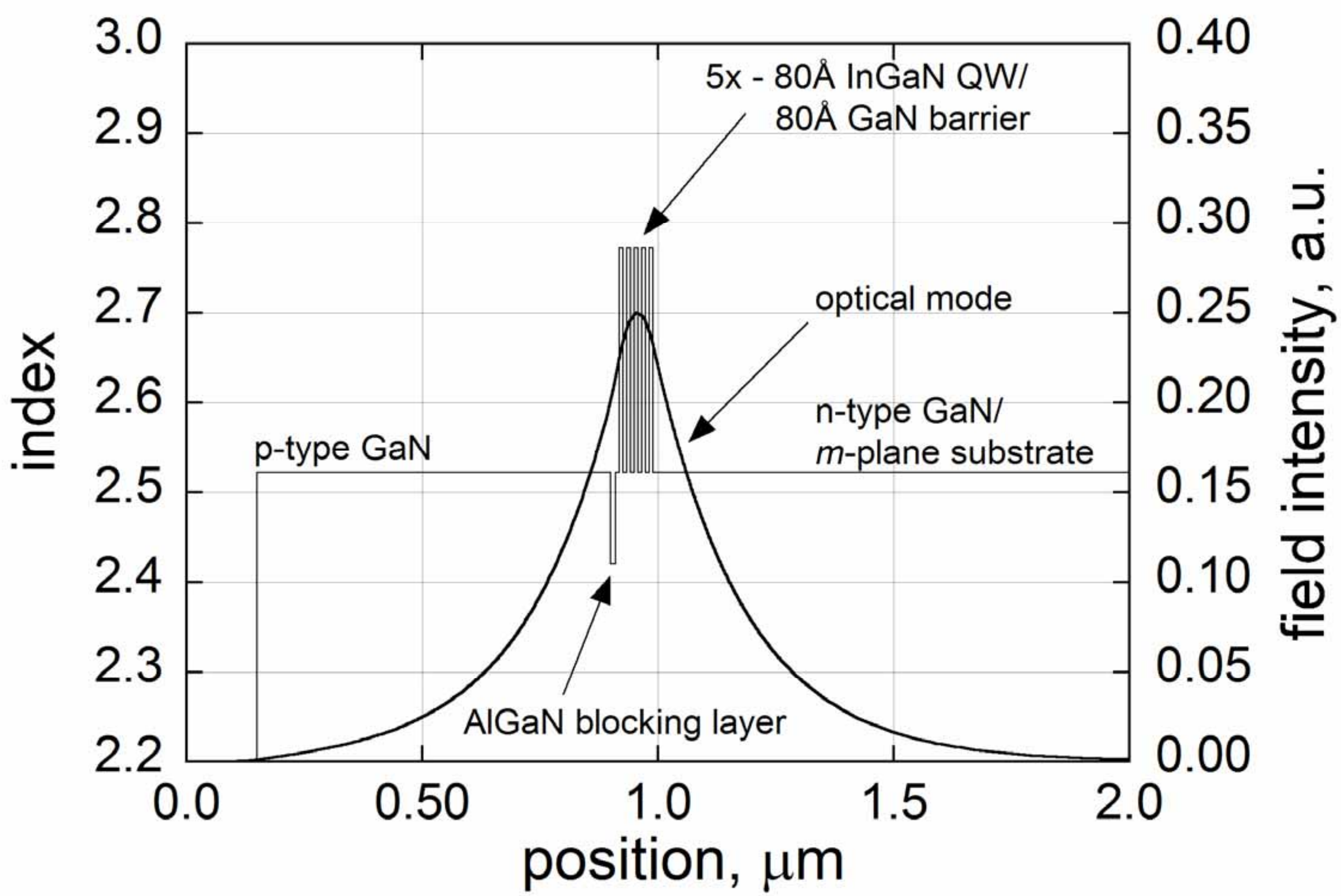
Conventional *c*-Plane Structures

- Thin (<4nm) QW required due to QCSE
- Parasitic waveguide (device surface – GaN/substrate interface)
- Thick AlGaN waveguide cladding layers required
  - Difficult growth of superlattices or highly strained thick AlGaN
  - Increased cracking from tensile strain
  - Higher voltage operation
  - Reduced lifetime and yield

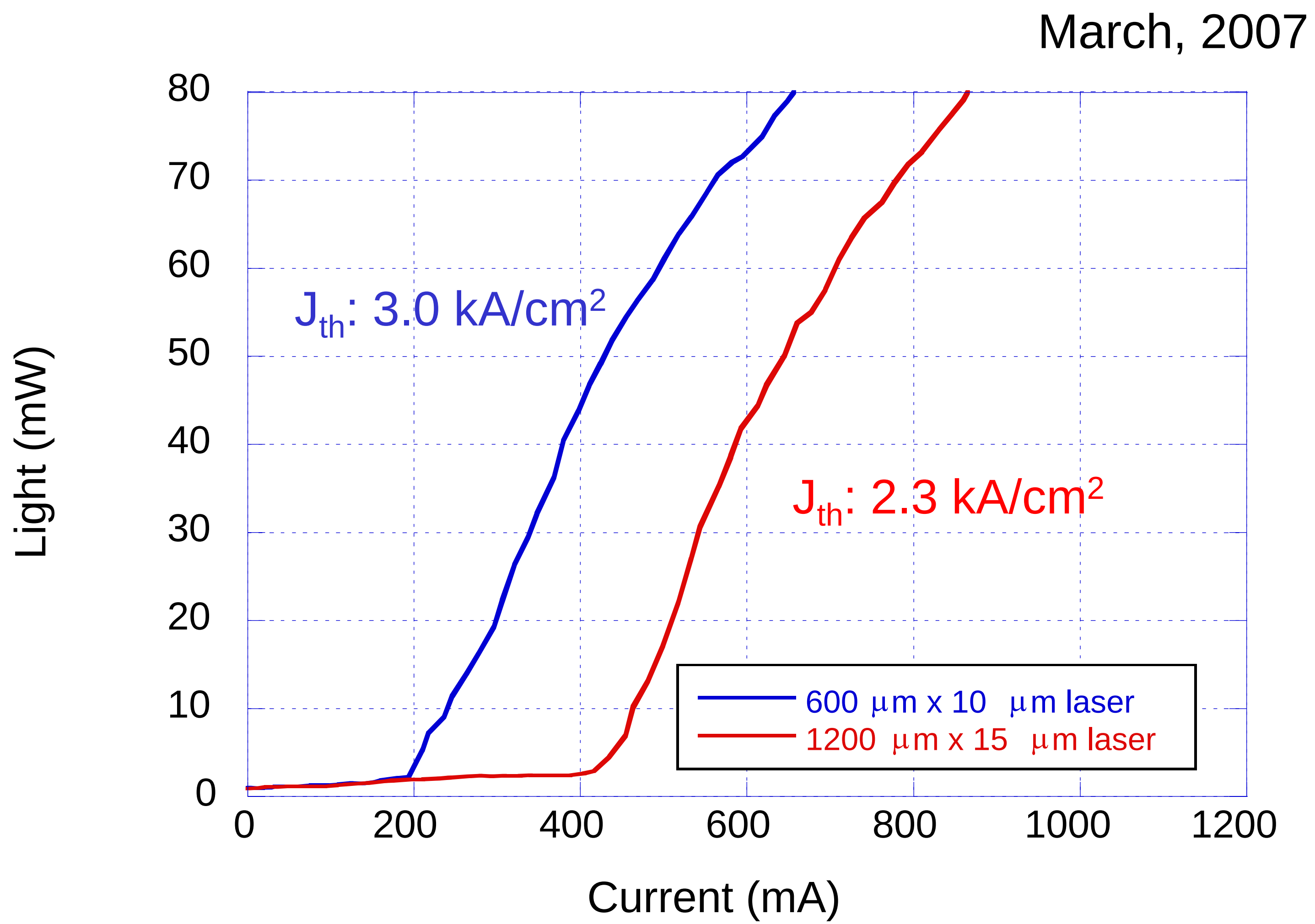


Mode Profile

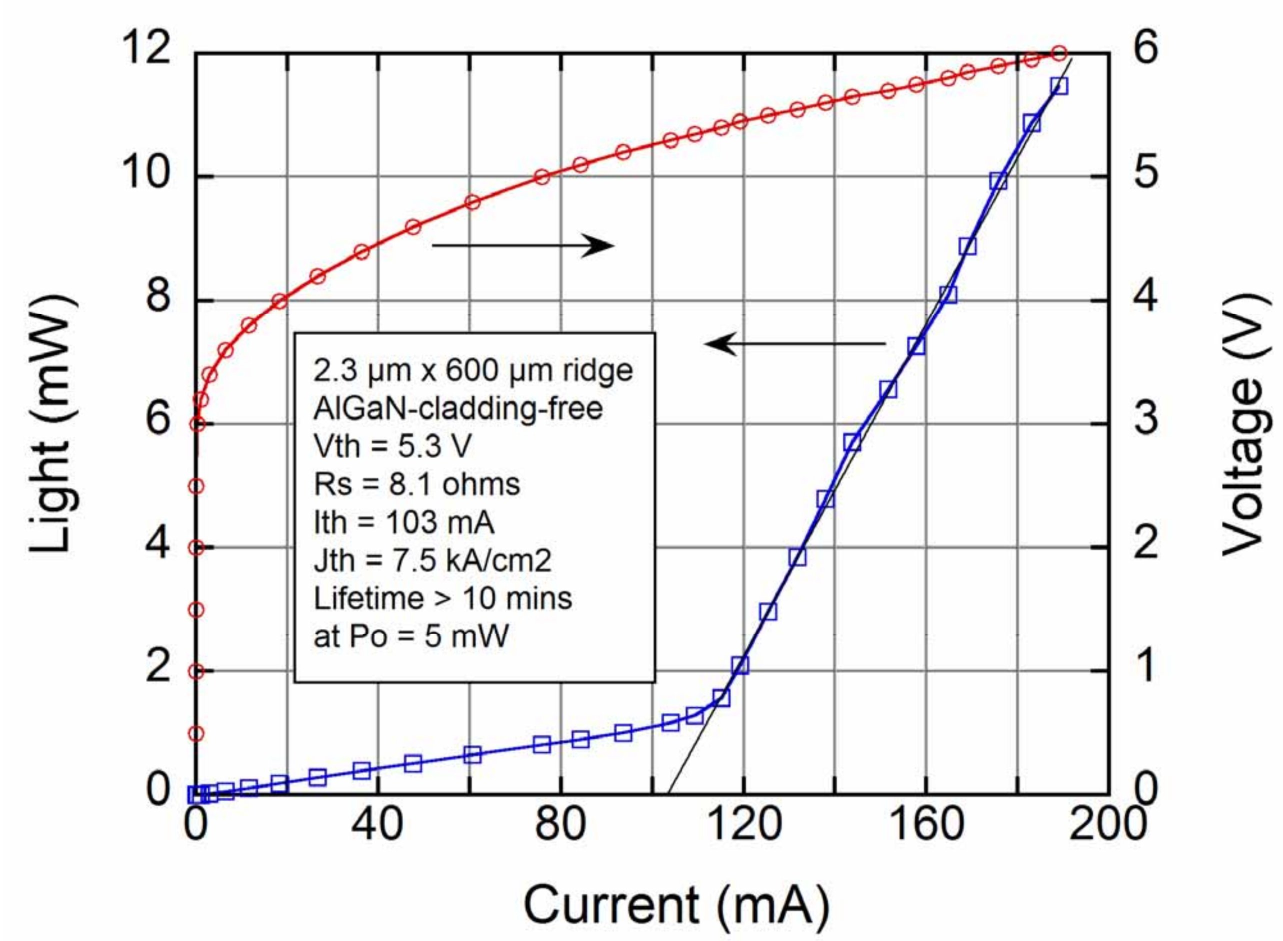
Transverse confinement factor is 16.4%



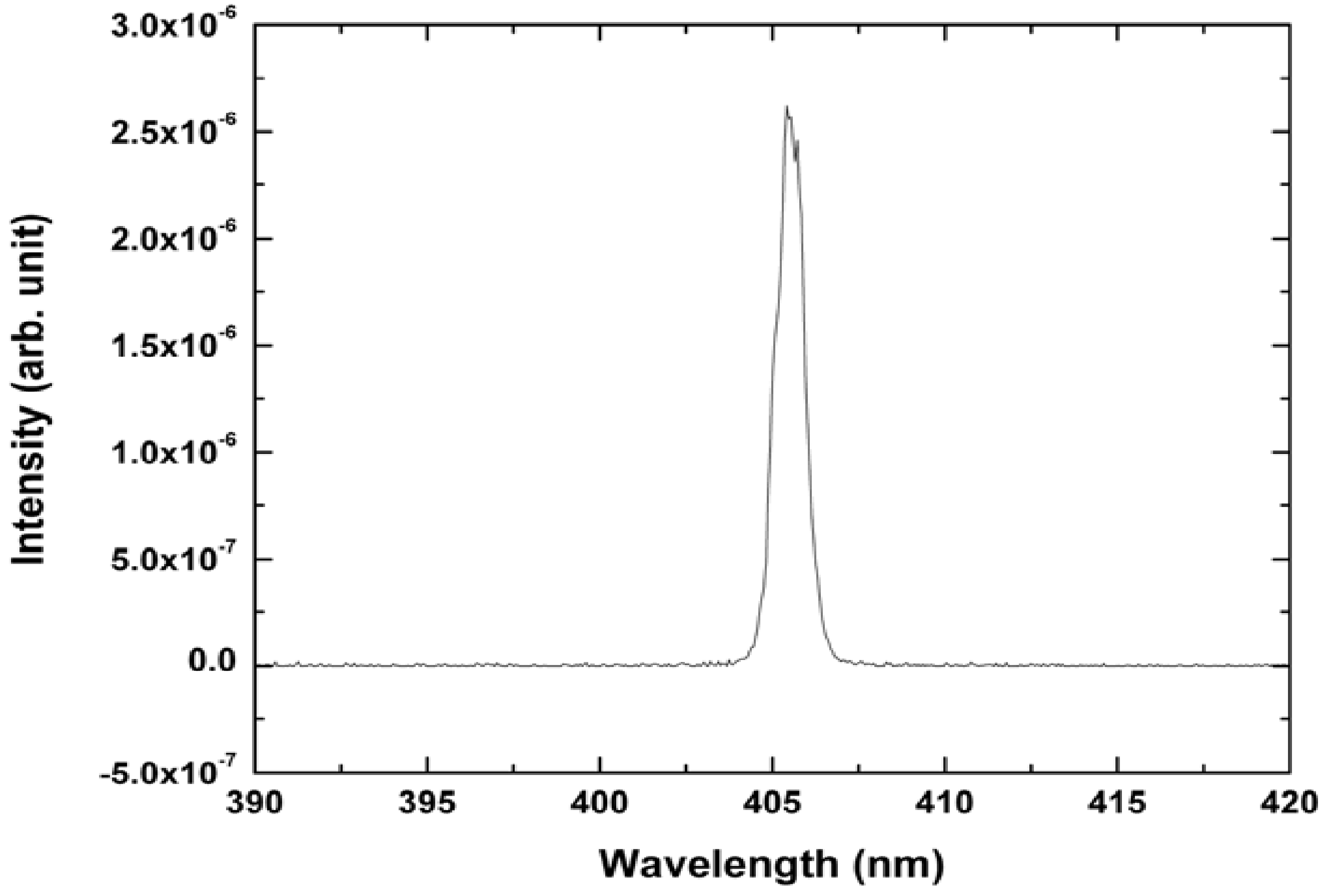
Broad Area Gain Guided Lasers



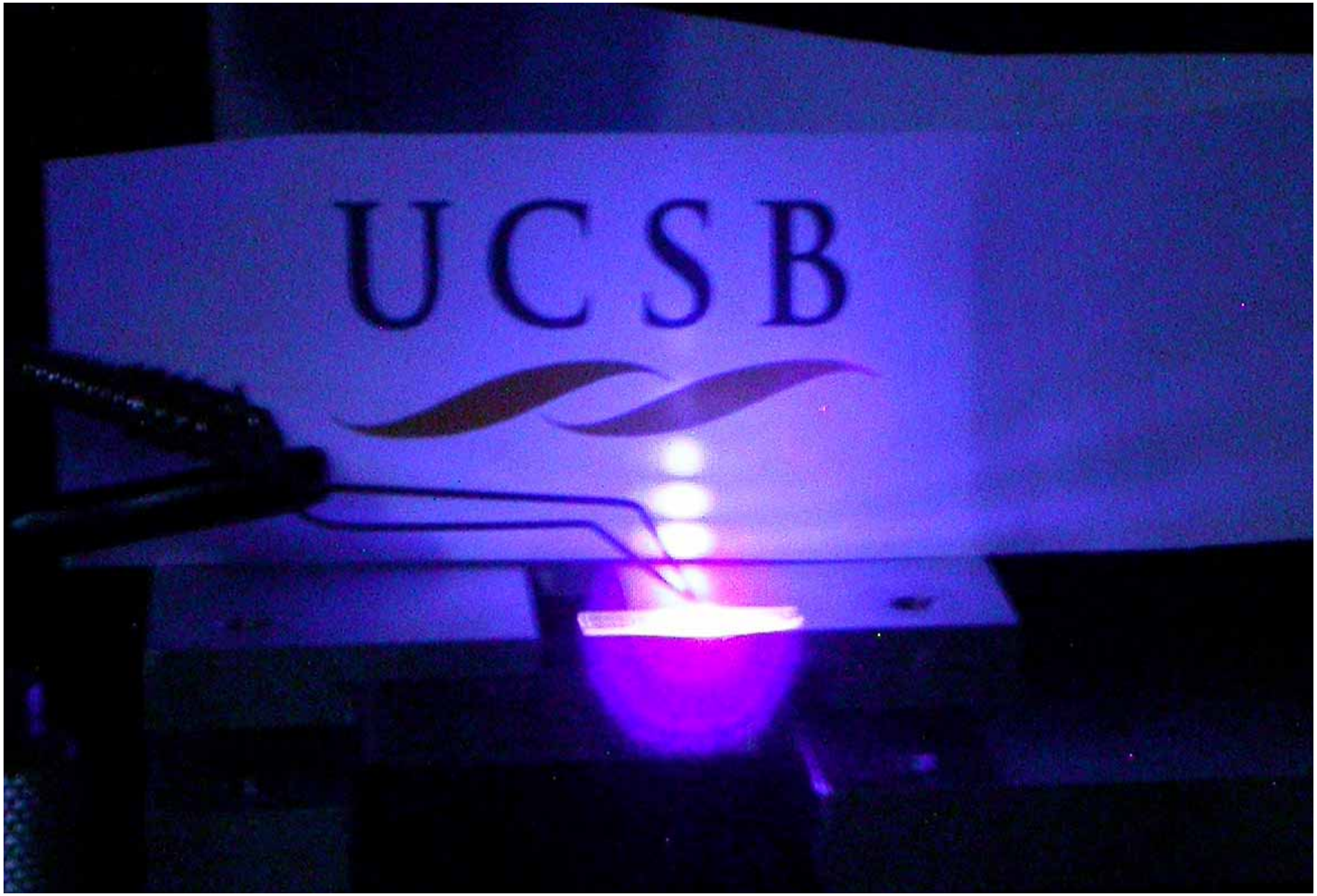
m-plane AlGaN-cladding-free CW LDs



Emission Spectrum of Nonpolar Laser Diodes



Far-Field Pattern of Nonpolar Laser Diode



Summary

- Nonpolar Laser diodes: Jth=2.3kA/cm^2
- Improved nonpolar LEDs from 0.1 mW to 28 mW over five year program
- Breakthrough->World-record nonpolar LED results
  - 28 mW @ 20 mA (45% EQE)
  - High polarization ratio = 0.57
  - Semipolar LEDs 21 mW @20 mA performance
- Developed *c*-plane InGaN LEDs
  - 32.4 mW @ 20 mA (57% EQE)
- Real bulk GaN crystal growth has been achieved
  - Crystal size 6-7mm
  - Large reactor –> large crystal