Advanced Nitride Materials for Ultimate Efficiency Solid State Lighting

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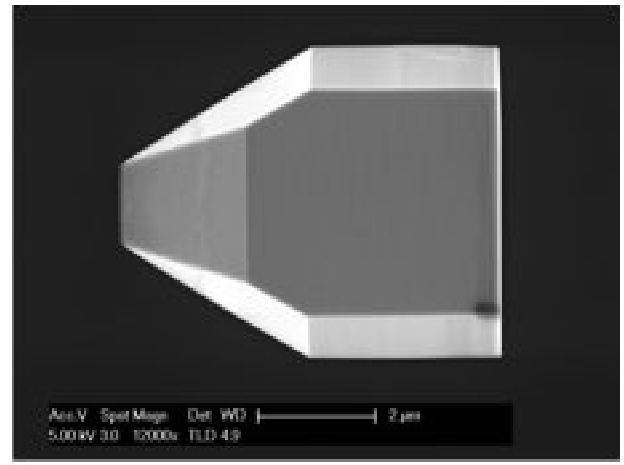


LEO of m-GaN from circular opening

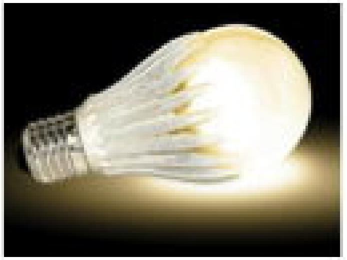
Core nitride faculty
S.P. DenBaars, U.K. Mishra, S. Nakamura, C. Weisbuch, C.G. Van de Walle

Outline

- Brief primer on light for lighting: not just photons and Watts
- Lighting: current technologies
- Solid state lighting
    - Challenges: efficiency and cost
    - Solutions: efficiency and cost
- Ultimate solid state lighting





Special thanks to M. Krames (Soraa) and D. Feezell (UCSB/UNM) for slides

Brief Primer on Light for Lighting:
Not just Photons and Watts

Light and Lighting – Definitions I (… *confusing*!)

Radiometry (physics)

Φ_e — Radiant flux – energy flow (W)

$I_e(\lambda) = d\Phi_e/d\omega$ — Radiant intensity - (W/sr)

$S(\lambda) = d\Phi_e/d\lambda$ — Spectral power distribution (W/m)

Photometry (includes human response!)

$\boldsymbol{\Phi_v}$ — Luminous flux – **Lumens (lm)**

V(λ) — CIE luminous efficiency function

$$\Phi_v = 683 \text{ lm/W} \int S(\lambda)\, V(\lambda)\, d\lambda$$

K — **Luminous efficacy**
Lumens/optical watt (lm/W)

$\eta_e = \Phi_e/P$ — Radiant efficiency (P = input power)

$\boldsymbol{\eta_v = \eta_e K}$ — **Luminous efficiency**
Lumens/electrical watt (lm/W)

Eye response V(λ)
Photopic - Cones

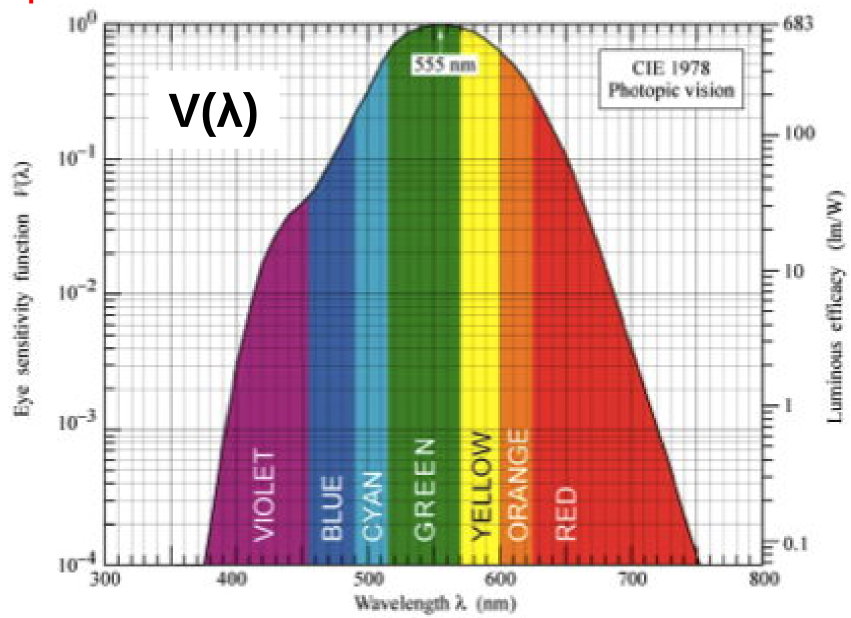


Fig. 16.7. Eye sensitivity function, $V(\lambda)$, (left ordinate) and luminous efficacy, measured in lumens per Watt of optical power (right ordinate). $V(\lambda)$ is greatest at 555 nm. Also given is a polynomial approximation for $V(\lambda)$ (after 1978 CIE data).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Lumen - Eye-weighted radiant flux

Light and Lighting – Definitions II

Lumen (lm): **Luminous flux** = Luminous intensity x solid angle
e.g., sphere 4π sr

A candle: 1 cd x 4π sr = **12.6 lm**

100 W lightbulb: **~1300 lm** **(i.e, 13 lm/W)**

Correlated Color Temperature (CCT):
Apparent blackbody temperature of a light source

e.g, Incandescent bulb: CCT ~2800 K ‘Cold white: CCT ~5000+ K

Color Rendering Index (CRI):
‘Light quality’ – comparison of light source to a blackbody radiator with same CCT (based on light source reflectivity from 8 test samples …)

e.g, Incandescent bulb: CRI = 100 Na lamp: CRI = 10 - 20

*formally: luminous intensity at 555 nm of a source with a radiant intensity I(λ) of 1.46×10^{-3} W/sr

CIE Diagram and White Light

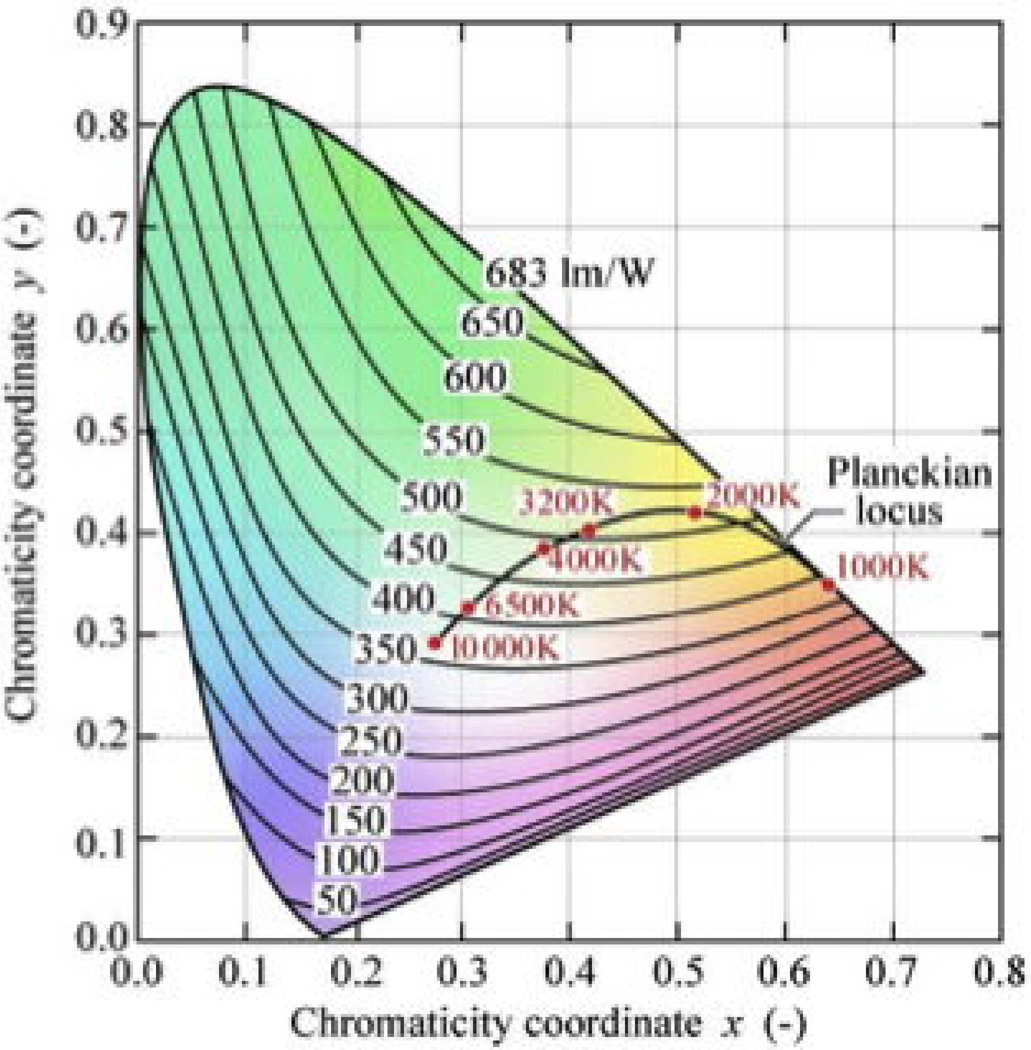


Fig. 16.8. Relation of maximum possible luminous efficacy (lumens per optical Watt) and chromaticity in the CIE 1931 *x*, *y* chromaticity diagram (adopted from MacAdam, 1950).

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

Lighting Technologies

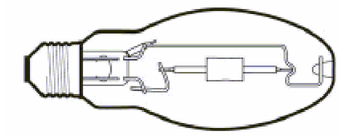
Conventional Light Sources

No Perfect Artificial Light Source Exists (yet)

Incandescent

Pros: Very cheap, great color
Cons: Very short lifetime, poor energy efficiency

High Intensity Discharge



Pros: Cheap, efficient
Cons: Poor color, long restart, short lifetime

Fluorescent

Pros: Cheap, energy efficient
Cons: Can not run in cold temp; difficult/costly to dim, control, Hg

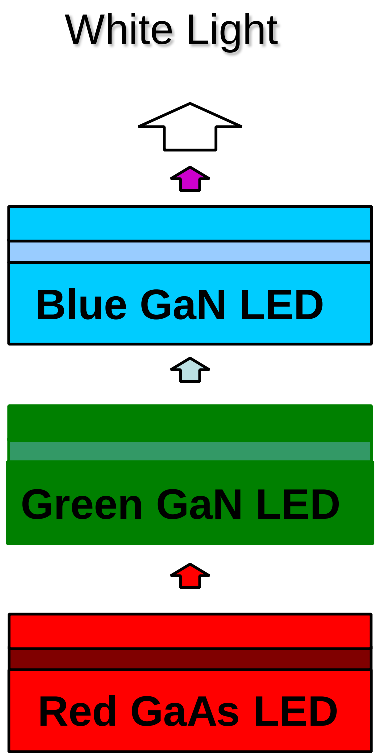
Compact Fluorescent

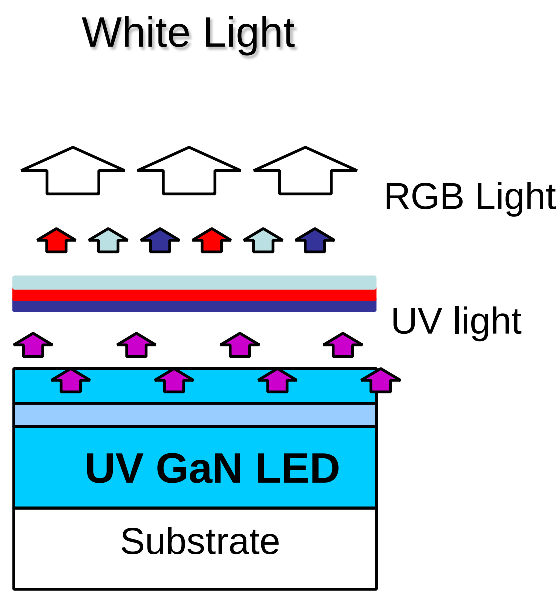
Pros: Energy efficient
Cons: Poor color quality, Can not run in cold, High cost vs. Incand, Hg

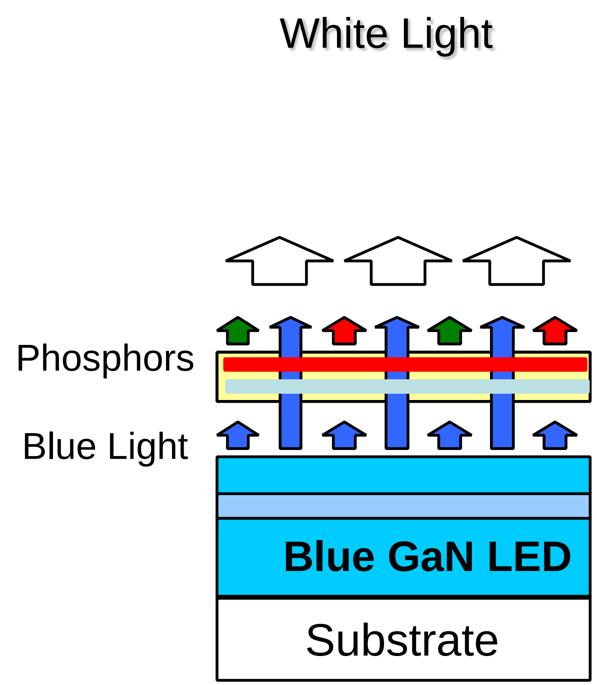
Halogen

Pros: Great color, focused light
Cons: Very short lifetime, poor energy efficiency

Three Methods of Making White Light with LEDs







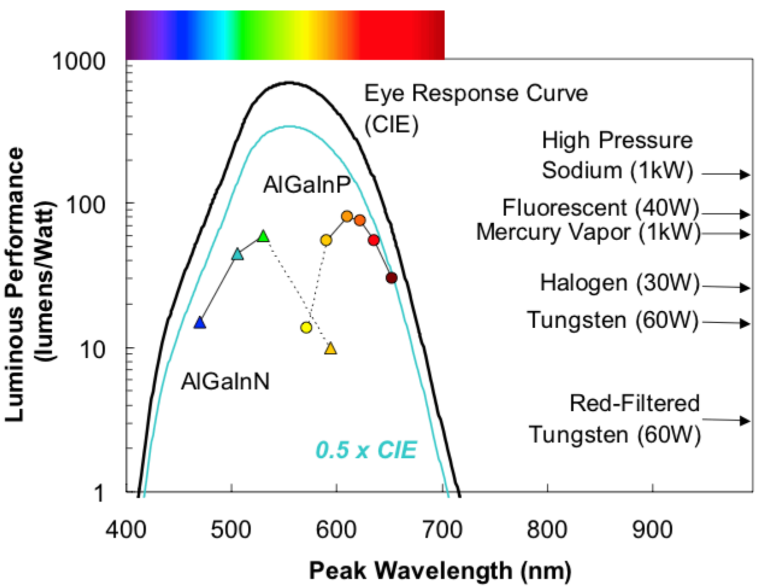
Multiple LEDs, RGB
- ~~good~~ efficiency
- highest cost
- tunable color

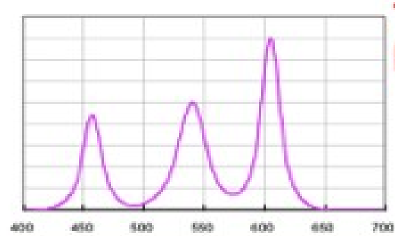
UV + Phosphors
- best CRI,
- color uniformity
- low cost
- lower efficiency
  -Phosphor conversion

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

Luminous Efficacy of a Source: lm/W

Goal 200 lm/W		50%		400 lm/W
Luminous Efficiency of a Source (lm/W)	=	**Wall Plug Efficiency**	X	**Luminous Efficiency of Radiation (lm/W)**
$\frac{\text{Luminous flux (lm)}}{\text{Electric power (W)}}$		$\frac{\text{Optical power (W)}}{\text{Electric power (W)}}$		$\frac{\text{Luminous flux (lm)}}{\text{Optical power (W)}}$





Theoretical maximum lm/W of a given source.

Determined only by the spectrum of the source.

Ideal LED SSL Efficiencies

Tradeoff between CCT, CRT and efficacy (lm/W)

Ideal: high CRI (100); low CCT (2700K); high lm/W!

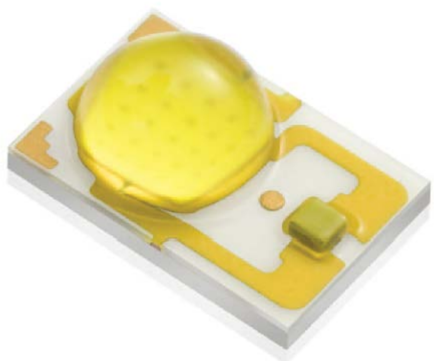
RGB White Light

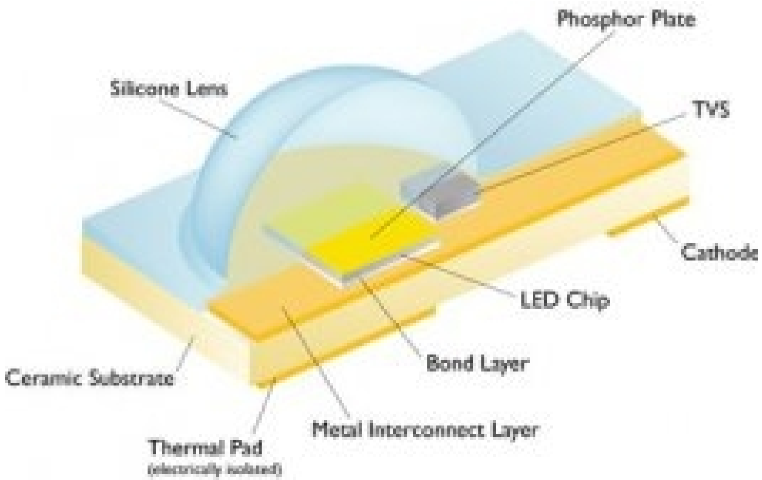
cm-LED	**Maximum LER**			**Efficacy for 67% Conversion**		
CCT	CRI 70	CRI 85	CRI 90	CRI 70	CRI 85	CRI 90
5000	380	365	356	255	245	239
3800	407	389	379	273	261	254
2700	428	407	**394**	287	273	264

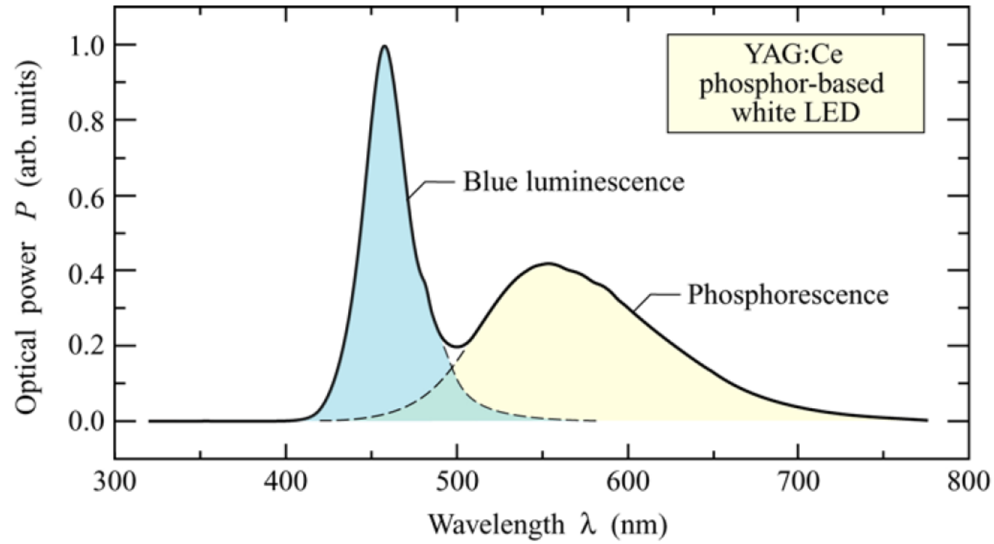
B + phosphor

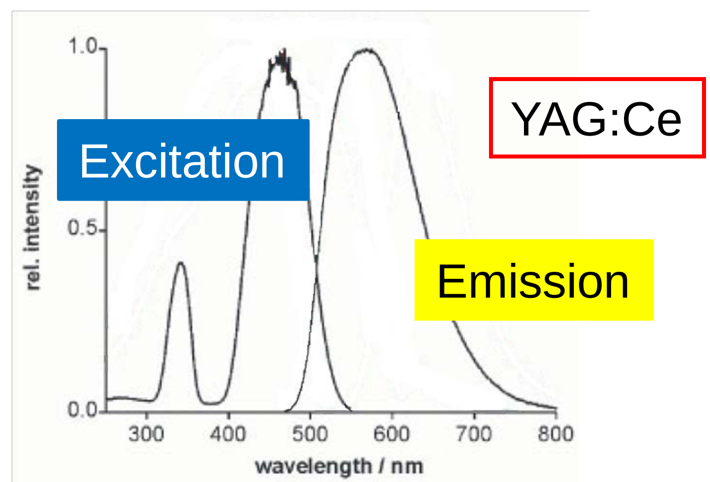
pc-LED	**Maximum LER**			**Efficacy for 54% Conversion**		
CCT	CRI 70	CRI 85	CRI 90	CRI 70	CRI 85	**CRI 90**
5000	350	337	332	189	182	**179**
3800	369	352	350	199	190	**189**
2700	**391**	**371**	**363**	211	200	**196**

GaN LED + YAG:Ce Phosphor White LED Workhorse









http://www.philipslumileds.com/technology/thermal

E. F. Schubert, *Light-Emitting Diodes,* 2nd ed. (Cambridge University Press, Cambridge, 2006).

Philips Lumileds - DOE L-Prize A19 Bulb

PHILIPS

DOE L-Prize Winner:

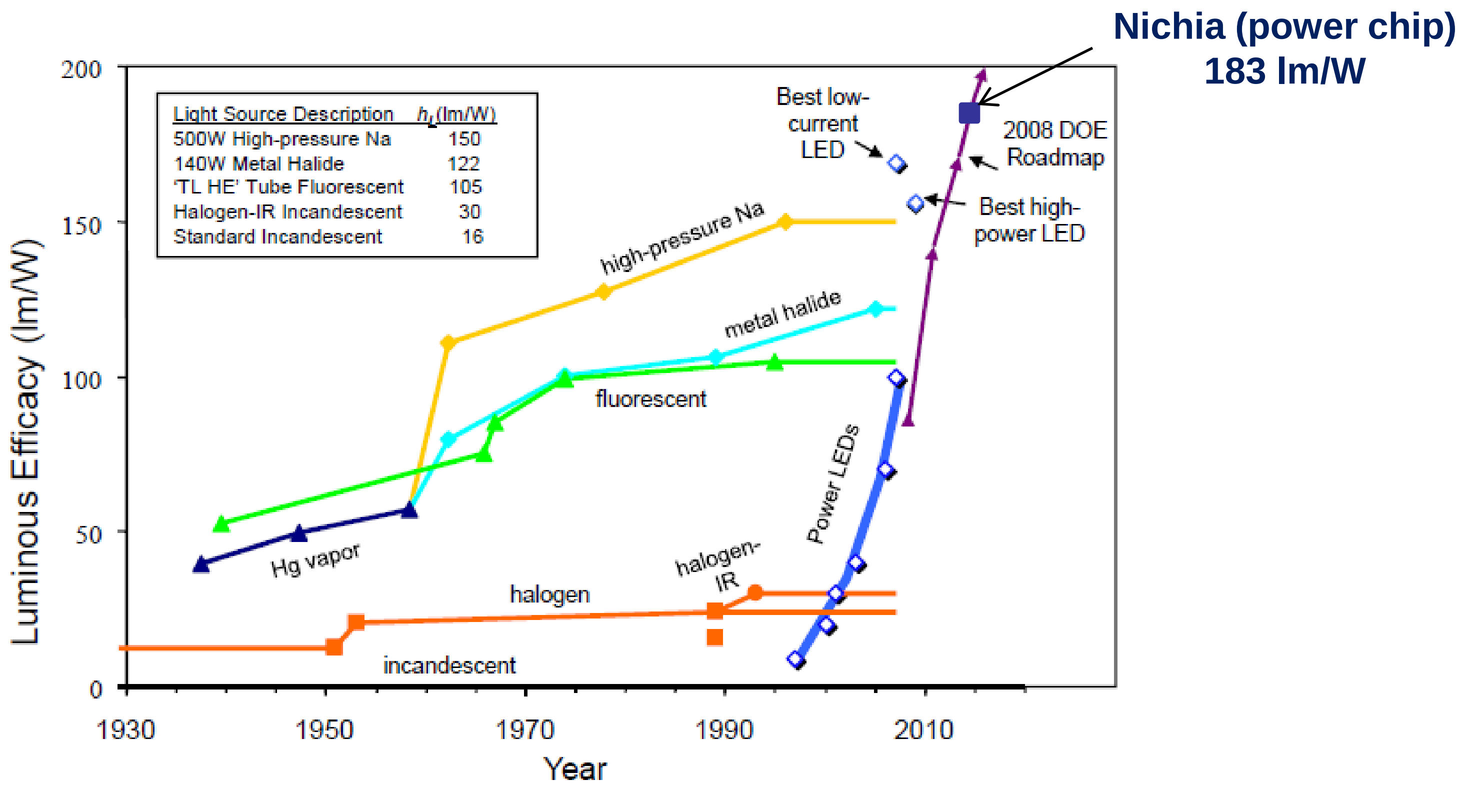
10 W; 940 lm (**94 lm/W**); CRI = 92; CCT 2700 K; 25,000 h life

Includes blue *and* red LEDs

$49.97 @ homedepot.com (Sept. 27, 2012)

~$20 for lower lm/W, lower CRI version

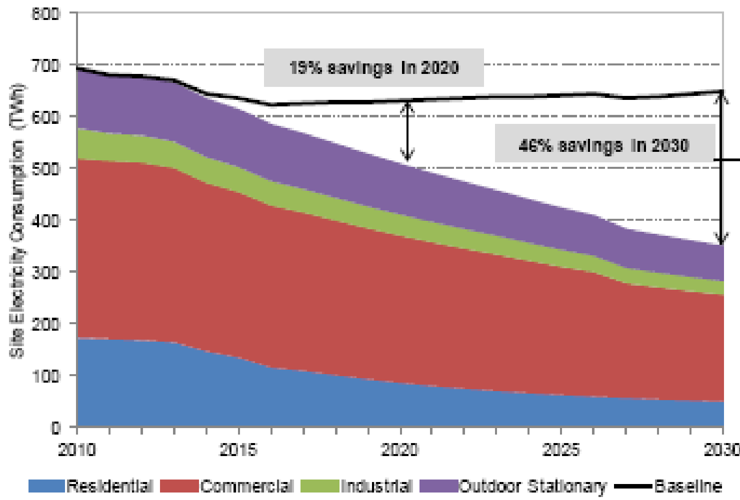
White LEDs vs. Conventional Lighting



- Emerging > 100 lm/W phosphor converted white LEDs (power chips)
- Expect > 150 lm/W power LED performance within the next few years

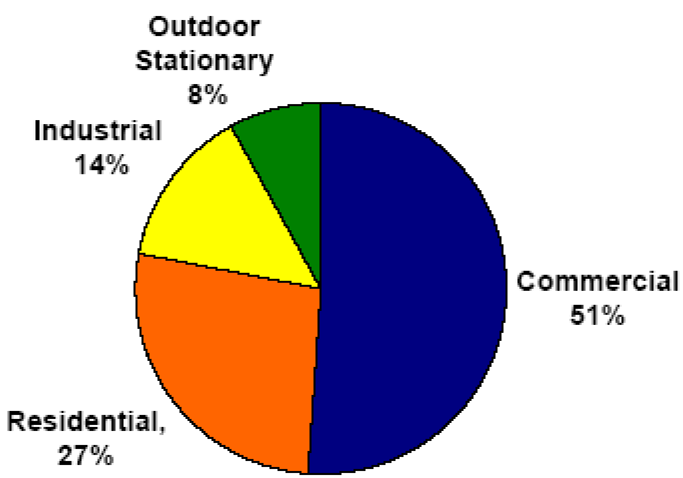
Lighting:
Energy and Economics

Impact of Solid State Lighting



46% savings with
LED lighting (150 lm/W)

Figure ES. 1 Forecasted U.S. Lighting Energy Consumption and Savings, 2010 to 2030



US Electricity Use
~20% for Lighting

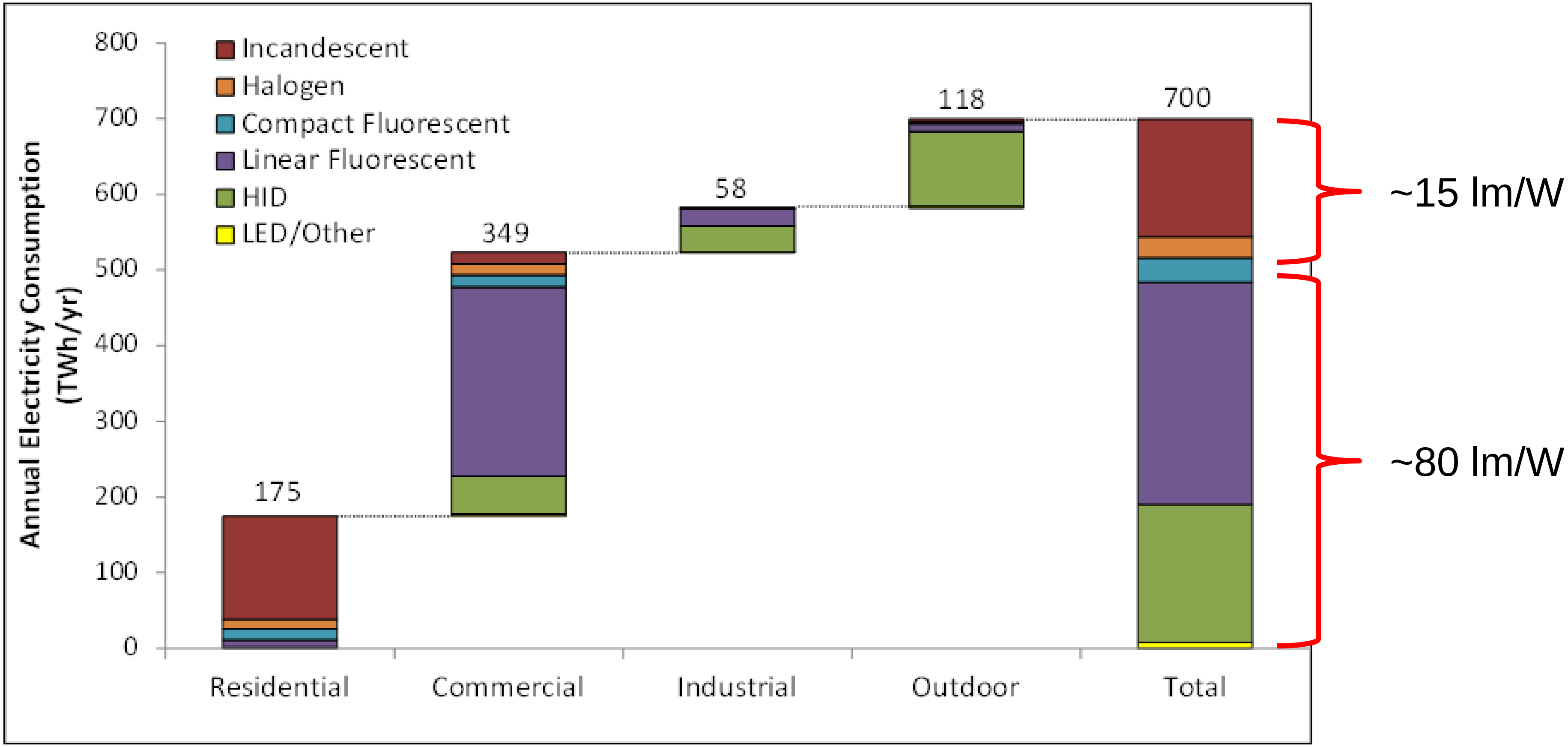
2030 Energy Savings from SSL in the U.S.

~300 TWh = ~10% of US electricity
(U.S. electricity generation ~500 GW)
= 50 GW power plants

Multiply 5x for world
(world electricity generation ~2500 GW)
= 250 GW power plants

DOE SSL MYPP 2012; IEA 2012 Key Statistics

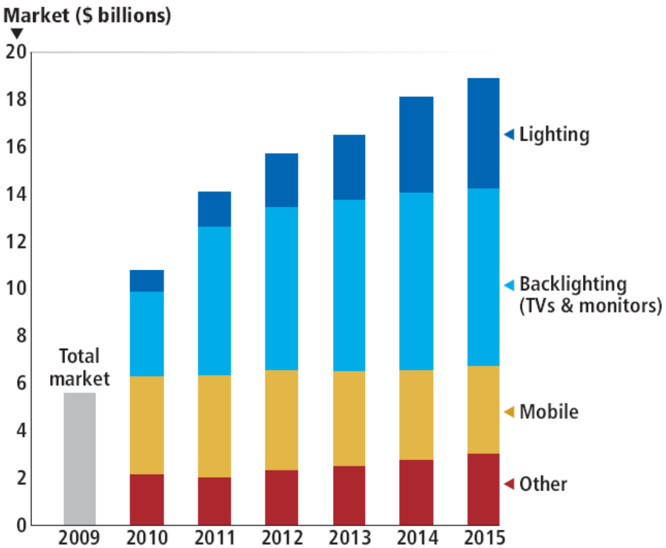
Lighting – U.S. Lumens Production



Linear fluorescent and HID, ~80-120+ lm/W: ~40,000 Tlmh/yr
Incandescent + halogen, ~15 lm/W: ~4,000 Tlmh/yr

***SSL ultimately needs >>100 lm/W to displace linear fluorescent and HID**

High Brightness LED Market



Source: Strategies Unlimited

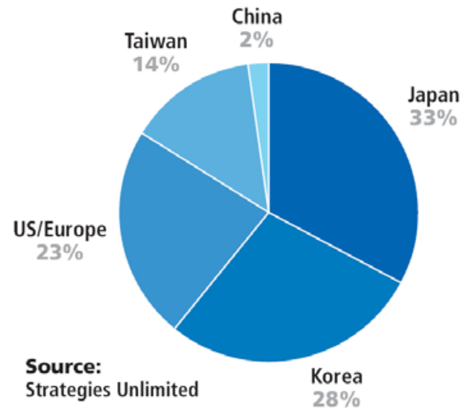


FIG. 2. HB-LED market in 2010 by country or region.

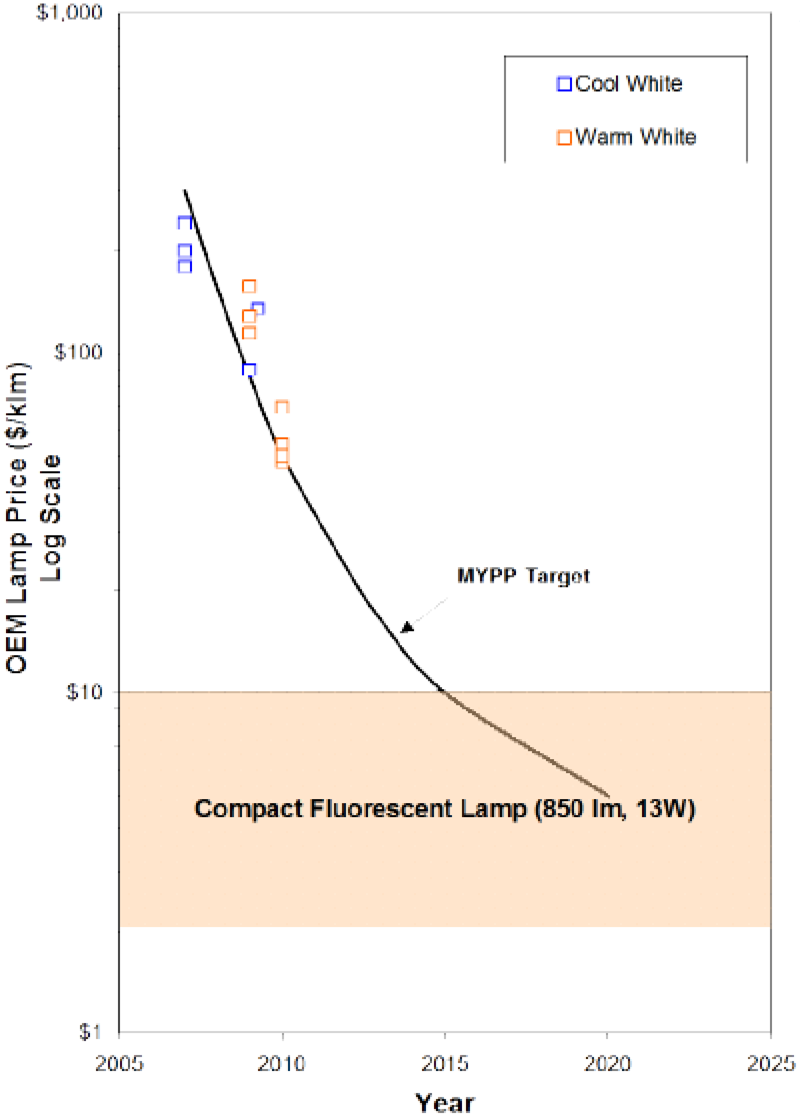
2010 ranking	HB-LED maker
1	Nichia
2	Samsung LED
3	Osram Opto Semiconductors
4=	Philips Lumileds Lighting
4=	Seoul Semiconductor
6=	Cree
6=	LG Innotek
8	Sharp
9=	Everlight
9=	Toyoda Gosei

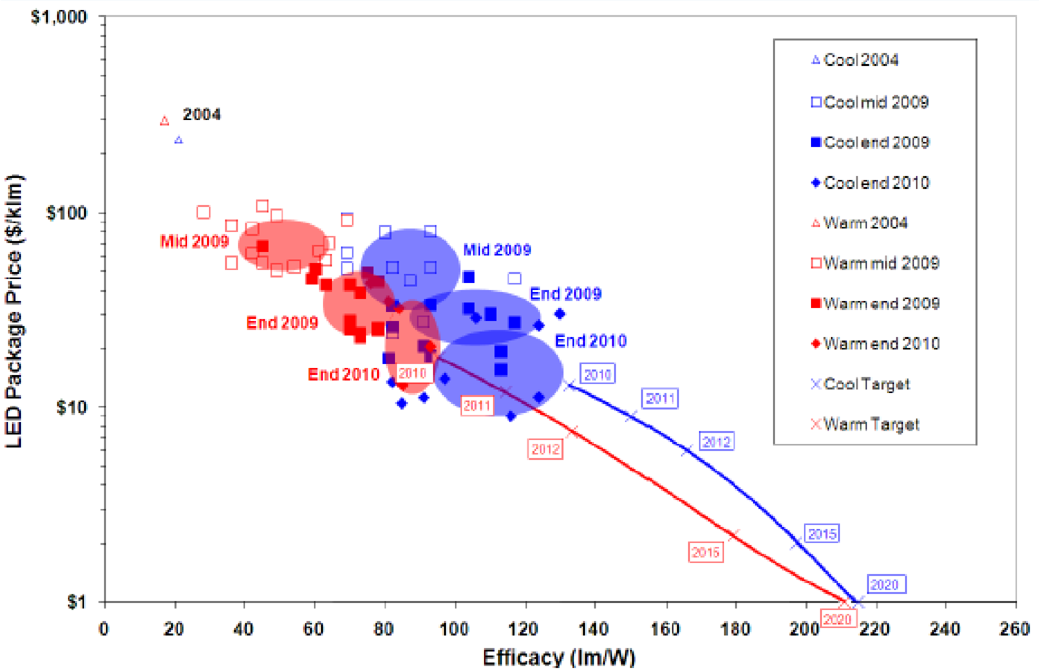
Source: Strategies Unlimited

FIG. 1. Ranking by revenue of the top 10 suppliers in the HB-LED market in 2010.

- Largest segment in 2010 was mobile (cell phones, mobile computing, mp3)
- Fastest growing segment was TV and monitor back lighting
- General lighting expected to drive the market by 2015
- Total available SSL market in 2020: ~$50B - $100B

SSL Economics – our 'Sunshot'!





SSL Targets for 2020

$1/klm cost

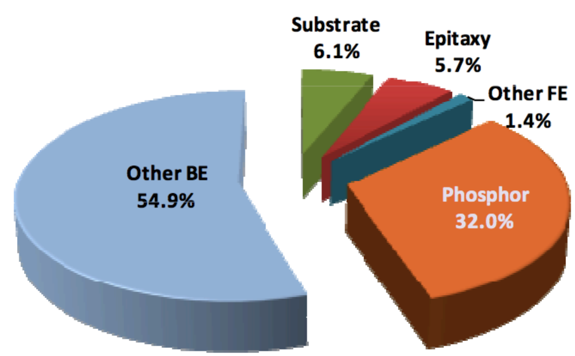
Industry targets

$0.50 light engine

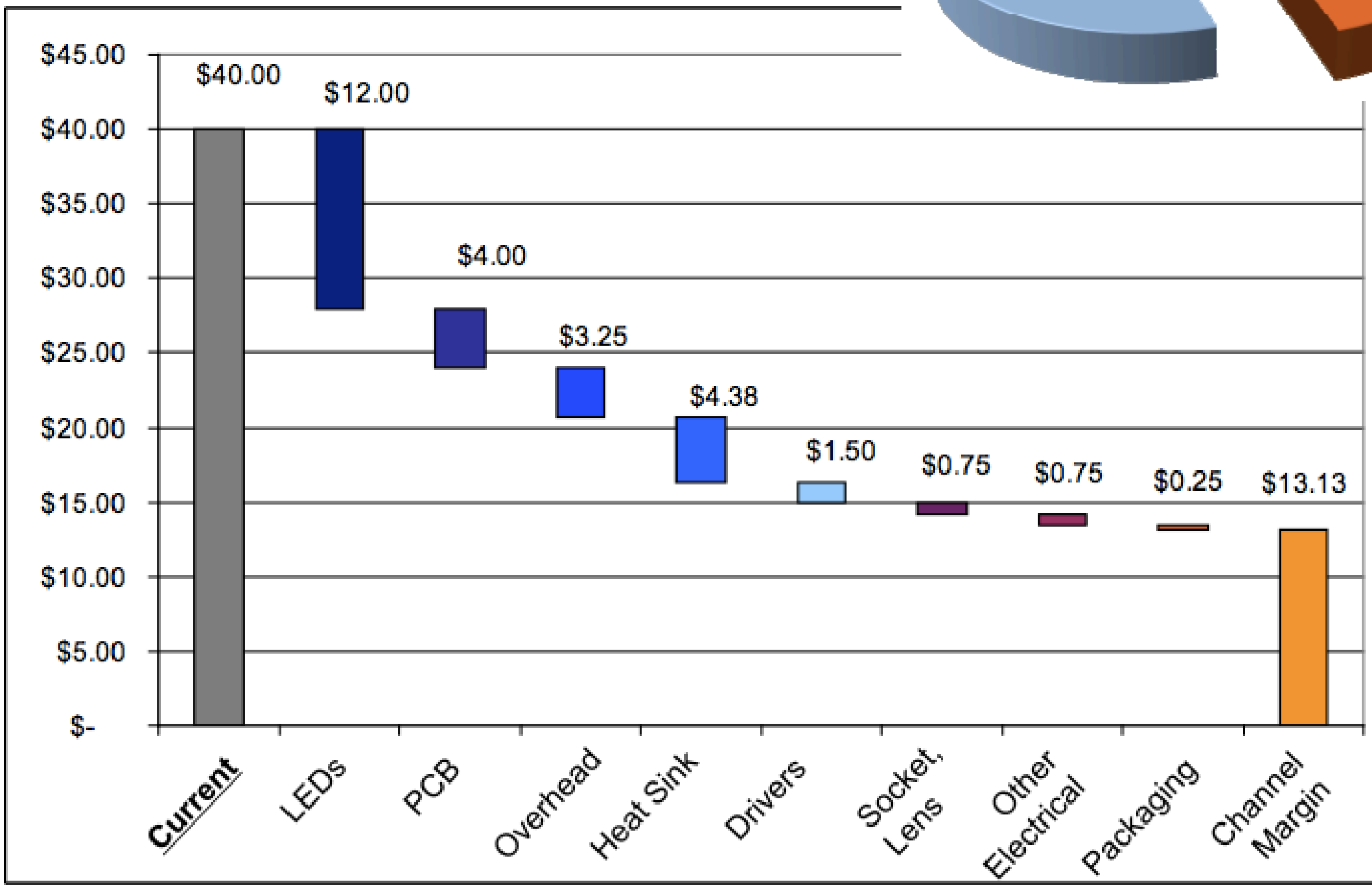
$0.50 electronics+base+luminaire …

$40 to $4 how does this happen?

Cost breakdown for 100k x 4" W/year



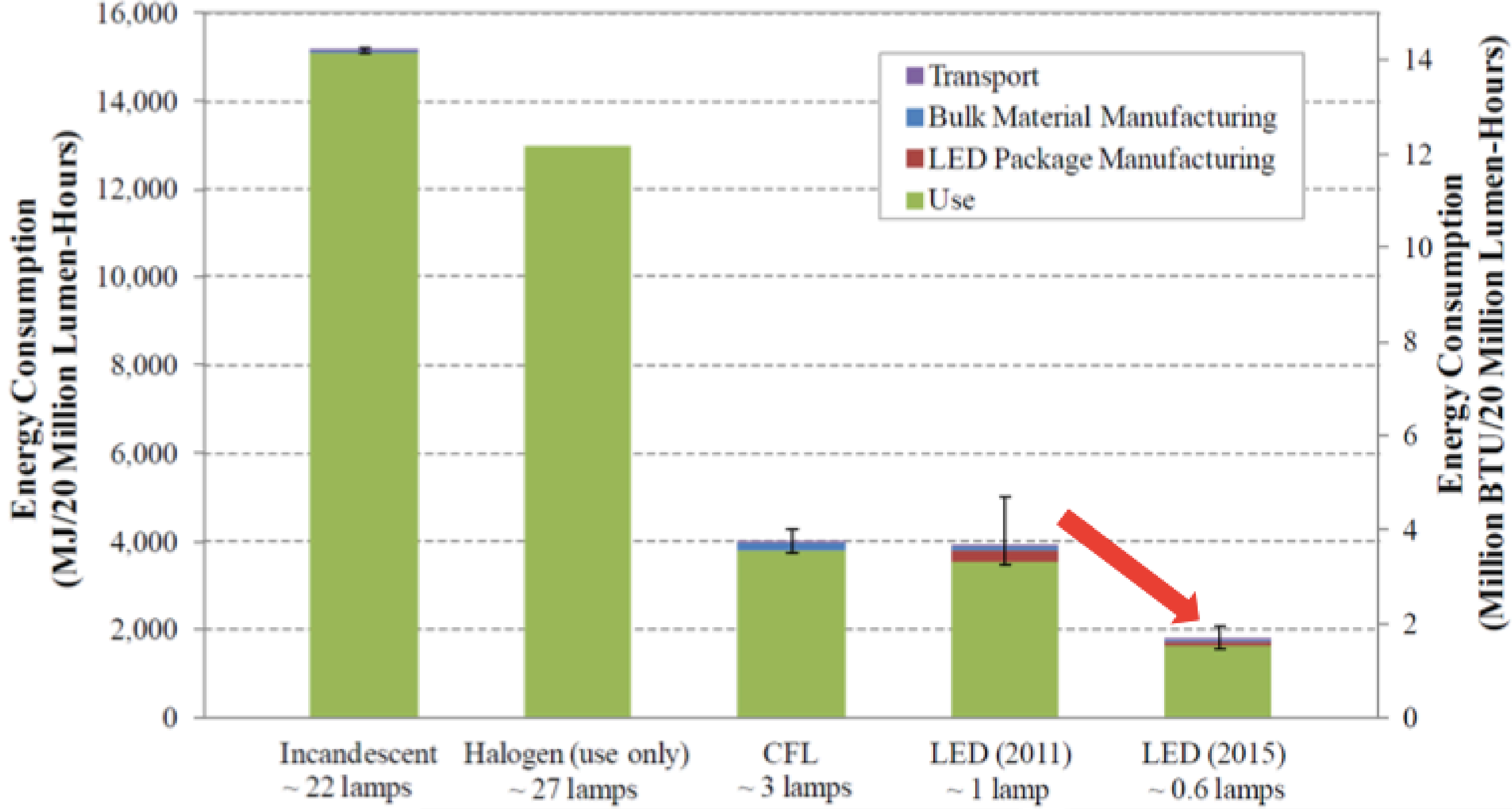
60W LED Lamp Bill of Ma



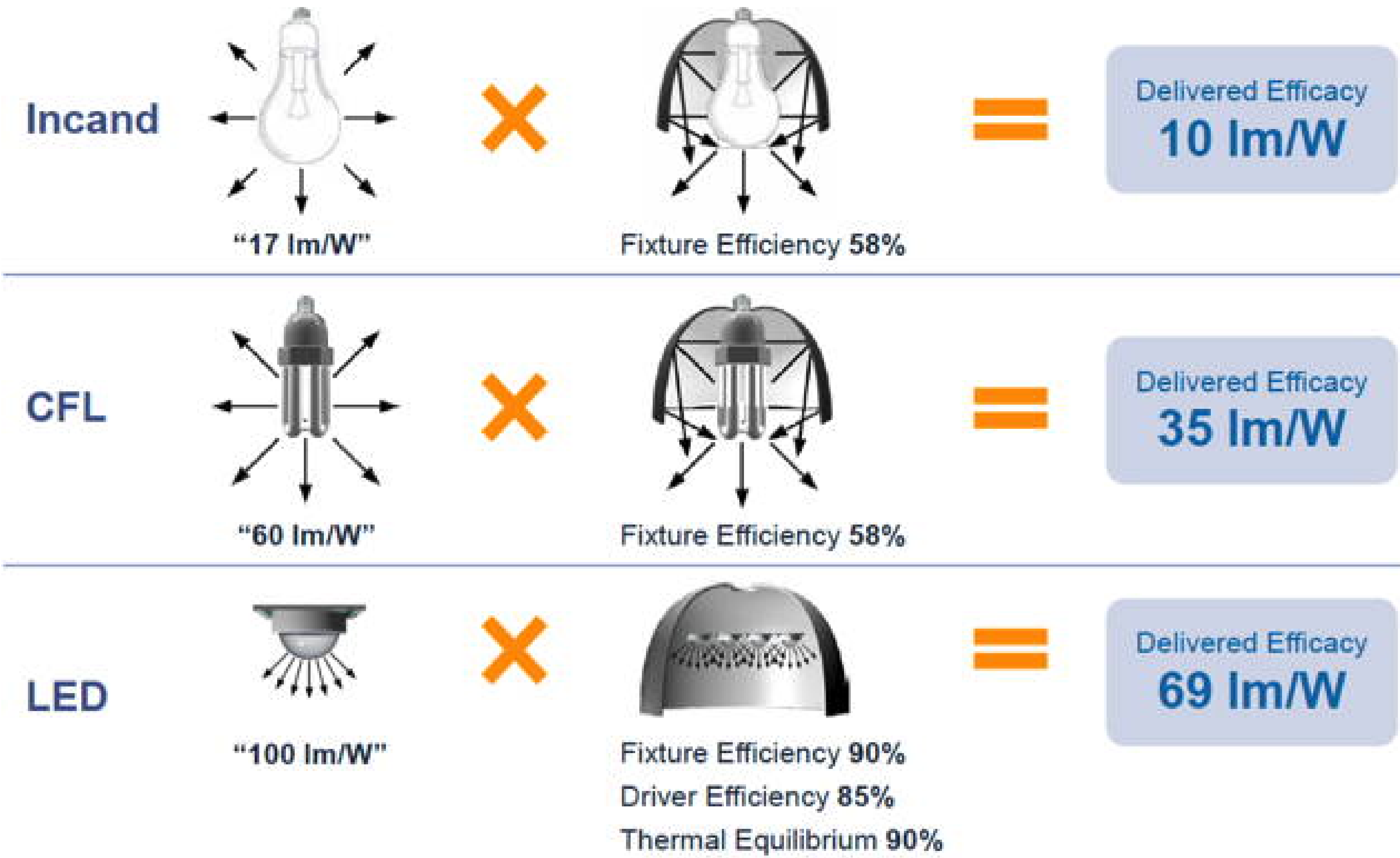
Jed Dorsheimer
Canaccord Genuity
7/18/2012

Source: Canaccord Genuity

Life-Cycle Energy of Incandescent Lamps, CFLs, and LED Lamps (DOE, 2012a)



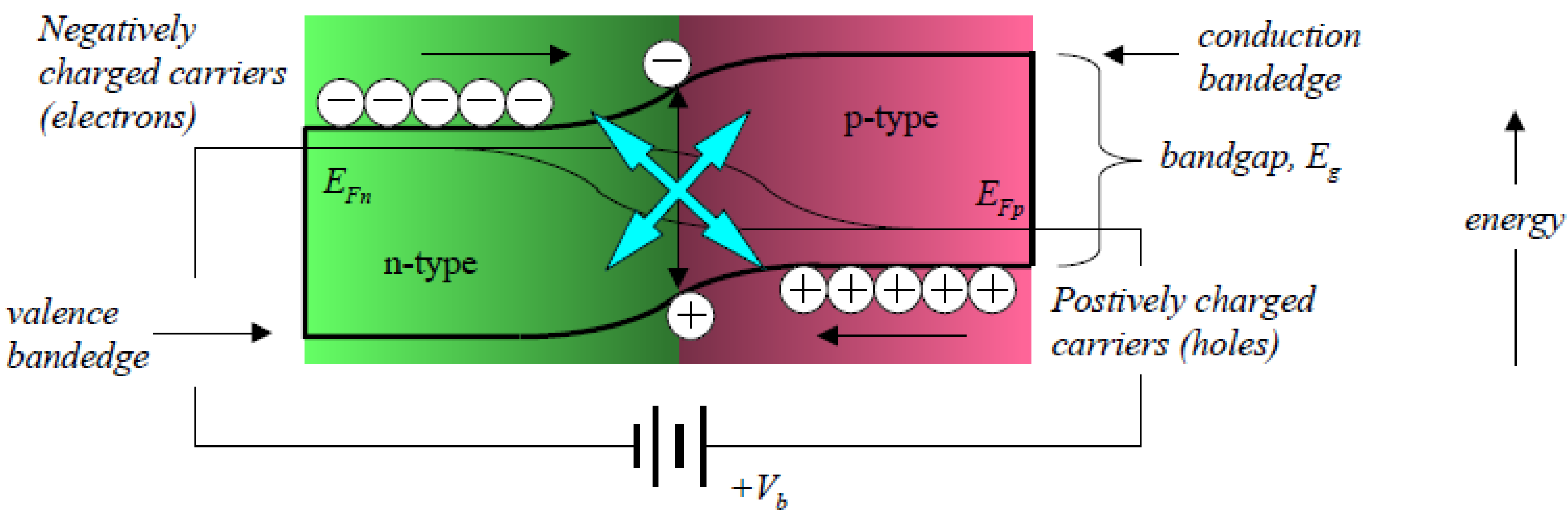
Overall System Efficiency



Solid State Lighting:

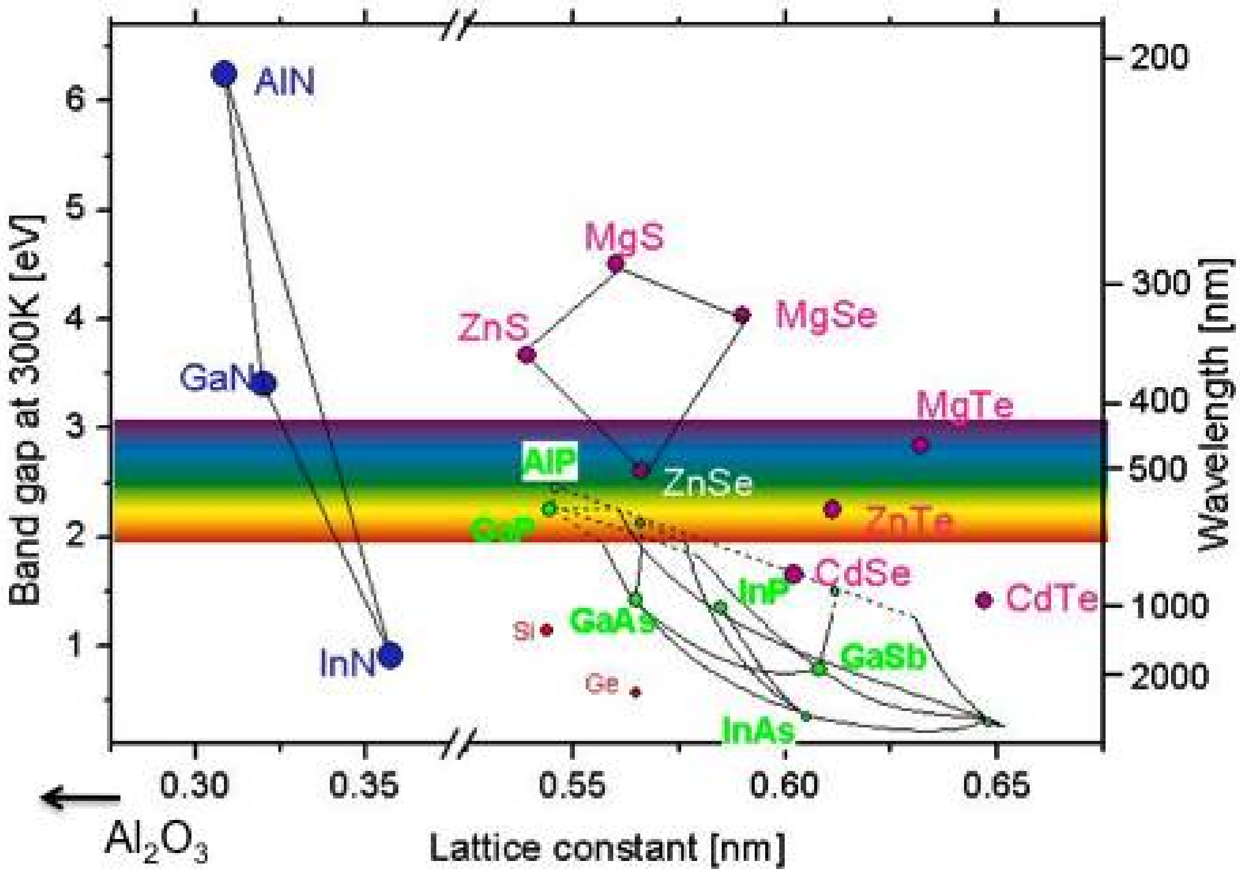
Materials and Devices

What is a Light Emitting Diode?



- Monocrystalline atomic arrangement determines semiconductor bandgap
  - Specifies optical properties
- Impurity doping provides p- and n-type regions
- At forward bias, injected electrons and holes recombine
- Energy may be released radiatively (light) or non-radiatively (heat)
- Fundamentally non-destructive

III-V Materials Systems for SSL



- (Al,Ga)InP system offers red (~650 nm) to yellow (~580 nm) emission
- (In,Ga)N system offers UV-A (~ 380 nm) to green (~550 nm) emission

Major Issues: Heteroepitaxy

C-plane GaN Heteroepitaxy

common to GaN/Al_2O_3; GaN/SiC; GaN/Si

Extended defects: Threading dislocations

Typical TD density $>10^8$ cm^{-2}

Stress:

Growth stresses

Island coalescence
Incomplete relaxation
Dislocation inclination
Mismatched layers

Thermal expansion mismatch (TEC)

Fundamental challenge

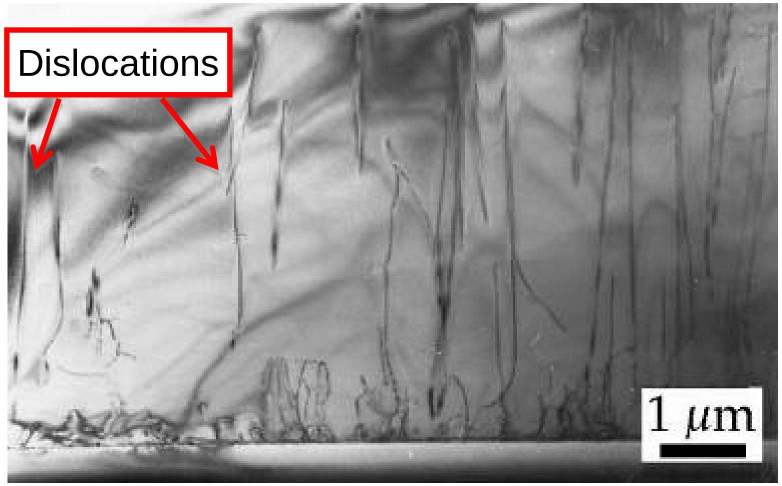
Nonpolar/Semipolar GaN Heteroepitaxy

Additional Extended defects:

Basal plane stacking faults

No known solution

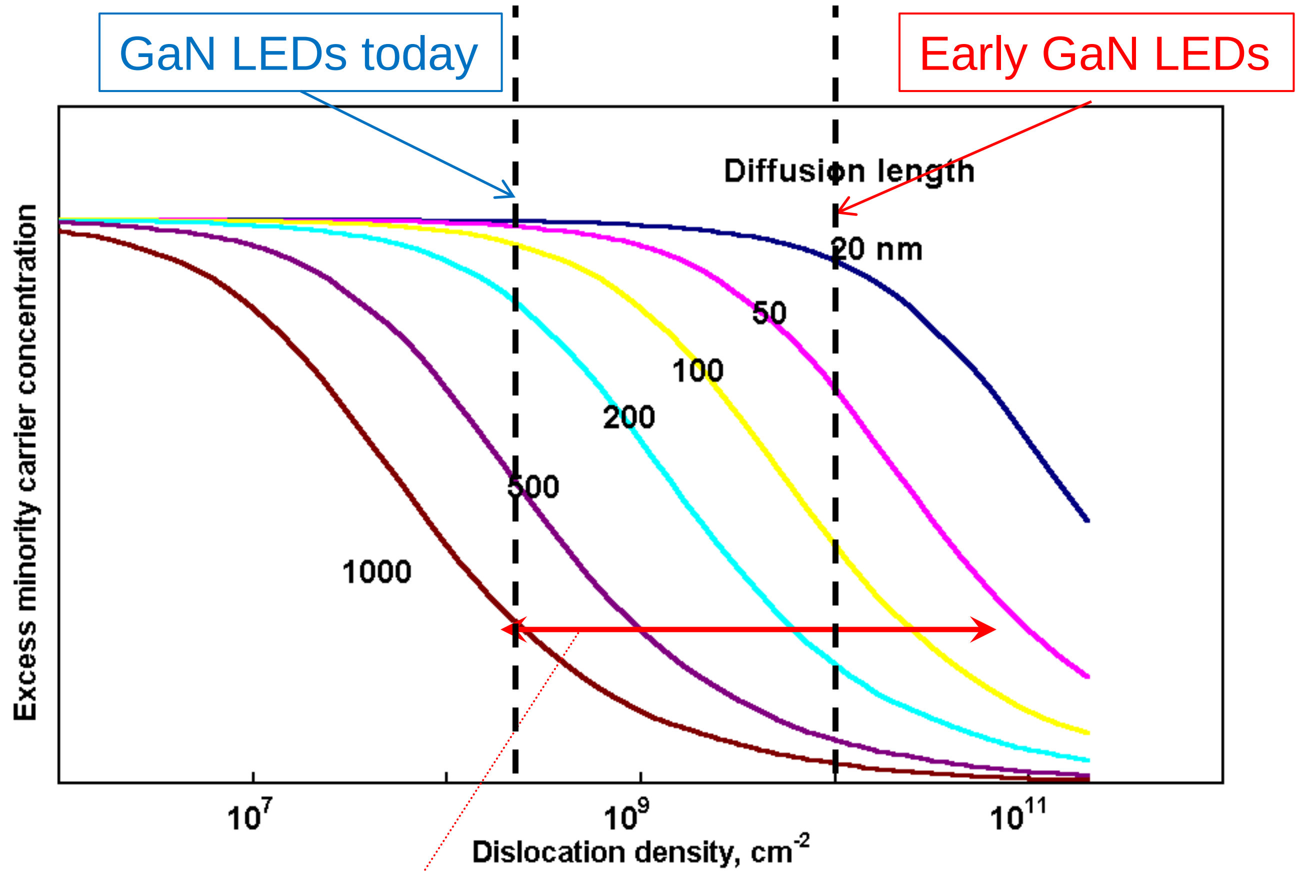
TEM of typical GaN on Sapphire



Typical GaN on sapphire
$\rho_{TD} = 5\text{x}10^8$ cm^{-2}

Excess Minority Carrier Concentration: Diffusion Length and Dislocation Density

Luminescence intensity is proportional to excess minority carrier concentration.

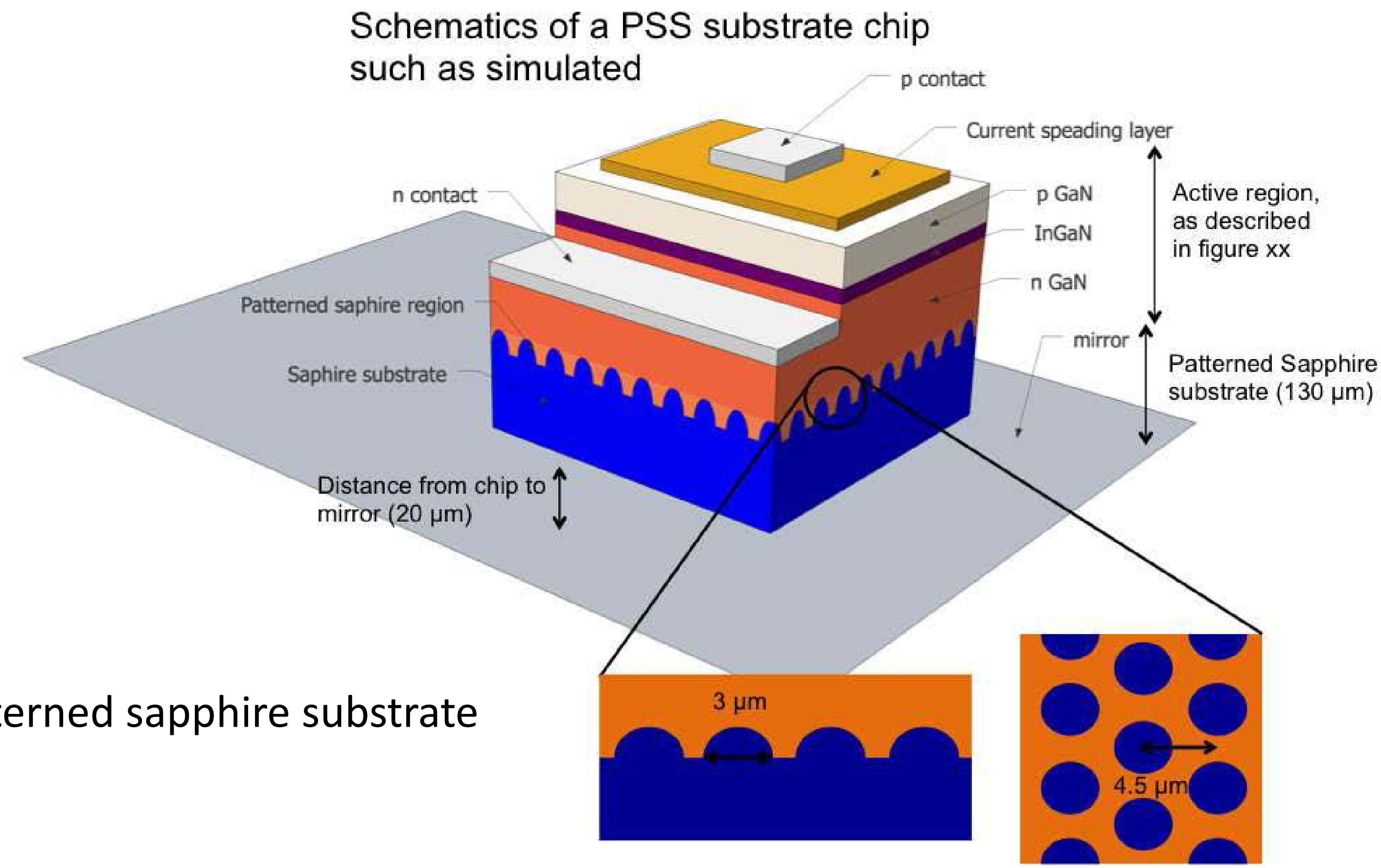


GaN: Minority carrier diffusion length: ~100 - 500 nm (common)

Compare TD densities: GaAs and InP (~10^3 cm^{-2}); Si and Ge (~10^0 cm^{-2})

 J.S. Speck and S.J. Rosner, *Physica B* **274**. 24 (1999)

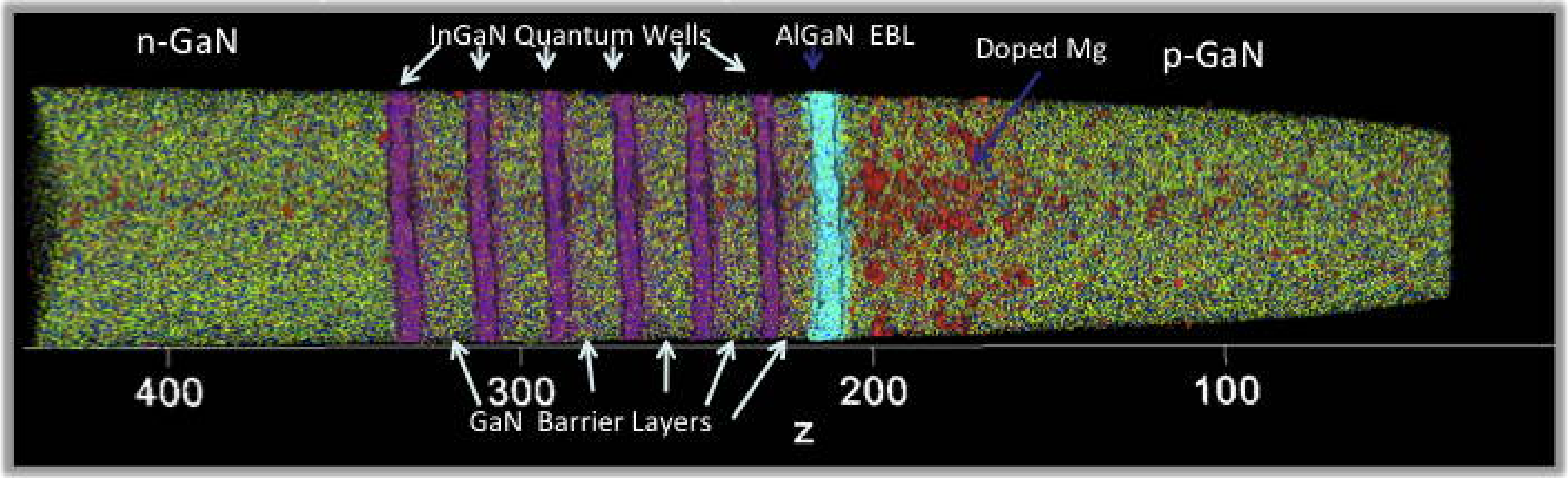
Typical GaN-Based LED Structure



Patterned sapphire substrate

Real Atomic Scale Structure of an LED!

UCSB m-GaN LED



GaN-Based LED Challenges:
Droop, Green Gap, Light Extraction

SSL Efficiencies –
Components of High Efficiency and the Challenges

LED Efficiencies

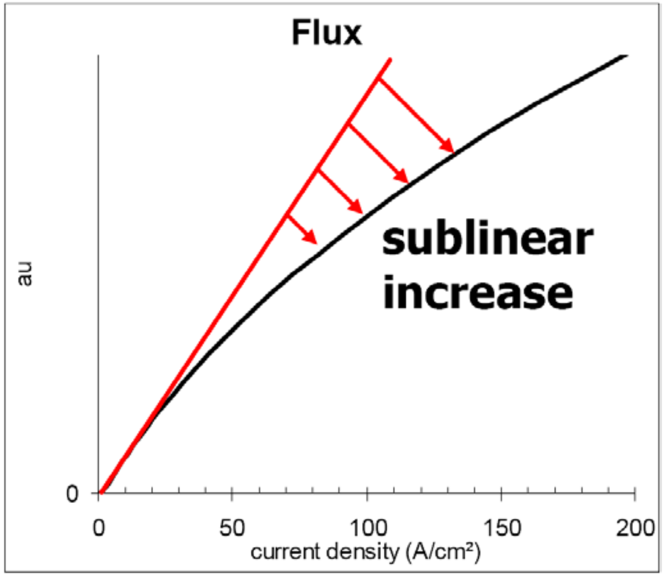
$$\eta_{tot} = \eta_{elec} \times \eta_{IQE} \times \eta_{extrac}$$

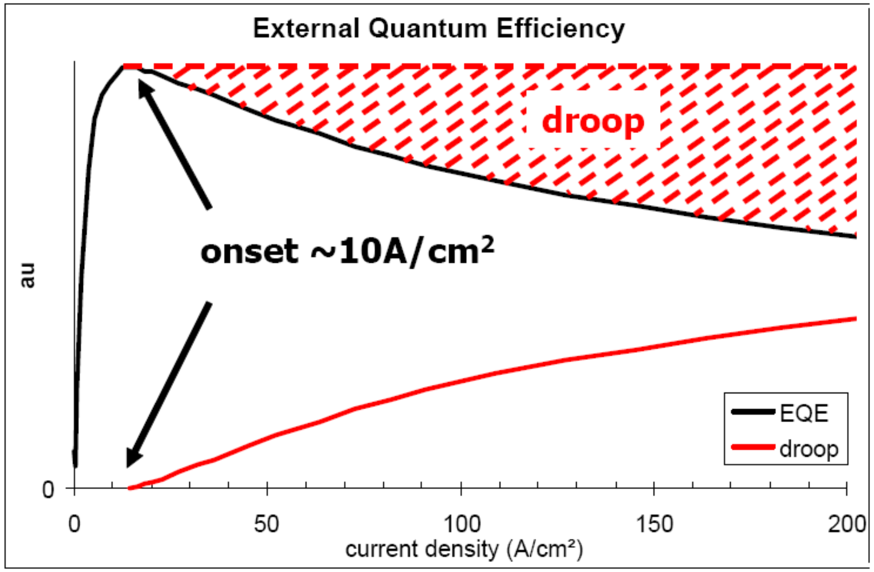
η_{elec} : **Electrical efficiency** … ohmic losses
Better contacts, doping, … ***Tunnel junctions***

η_{IQE} : **Internal quantum efficiency**: electron-hole pairs to photons
Major issues:
Droop (efficiency drop at increasing current drive)
Green gap

η_{extrac} : **Extraction efficiency**: escape efficiency for photons
Major issues:
Increase η_{extrac}
Directionality
Approaches here extend to system level issues

Efficiency Droop





InGaN-based LEDs

→ Peak EQE at 1 - 10 A/cm^2

Potential Cause:

1. Auger recombination: scales as n^3
2. Carrier leakage/overshoot
3. Delocalization of carriers

Solutions via ***wider*** quantum wells – not possible in current c-plane technology

Why Efficiency Droop Matters

1000 lm lightbulb today

10 LED die, 1 mm x 1 mm, 350 mA …. 35 A/cm^2
350 mA x 3 V = 1W
100 lm/W x 10 = 1000 lm

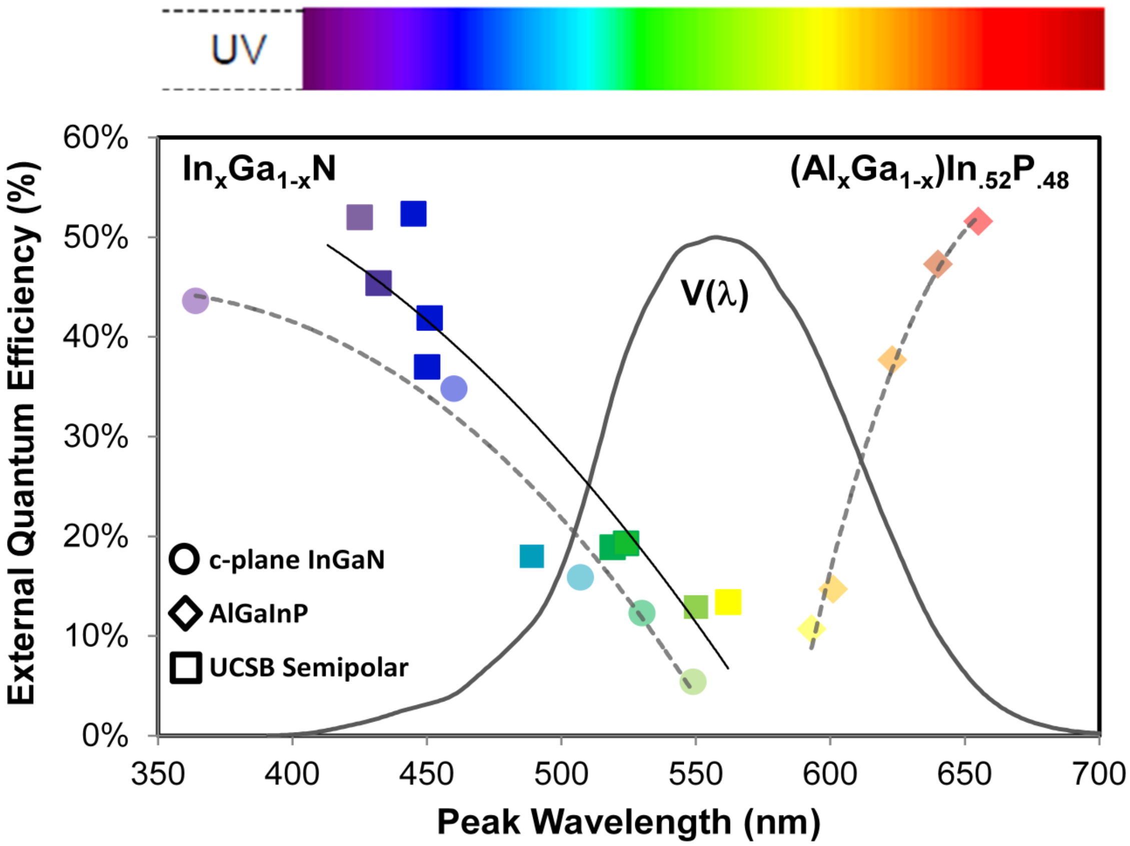
IF, we maintain efficiency at 10X current density

1 LED die, 1 mm x 1 mm, 3500 mA … 350 A/cm^2

10X reduction in LEDs, nearly all other cost go down

Solving droop: addresses efficiency AND cost

The 'Green Gap'

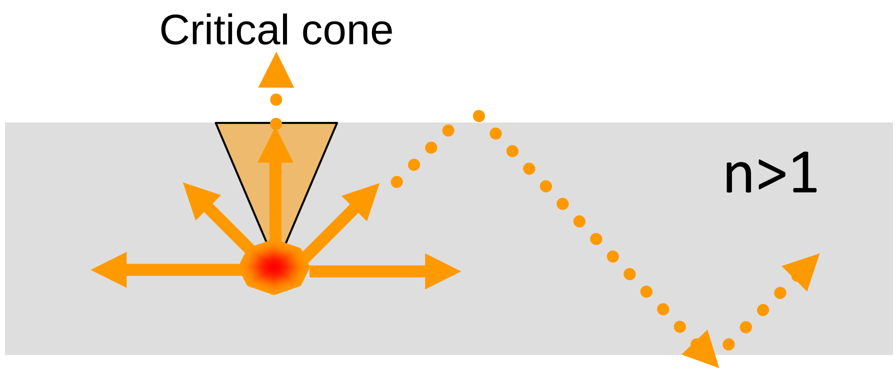


Semipolar LEDs may have the potential to solve the green gap

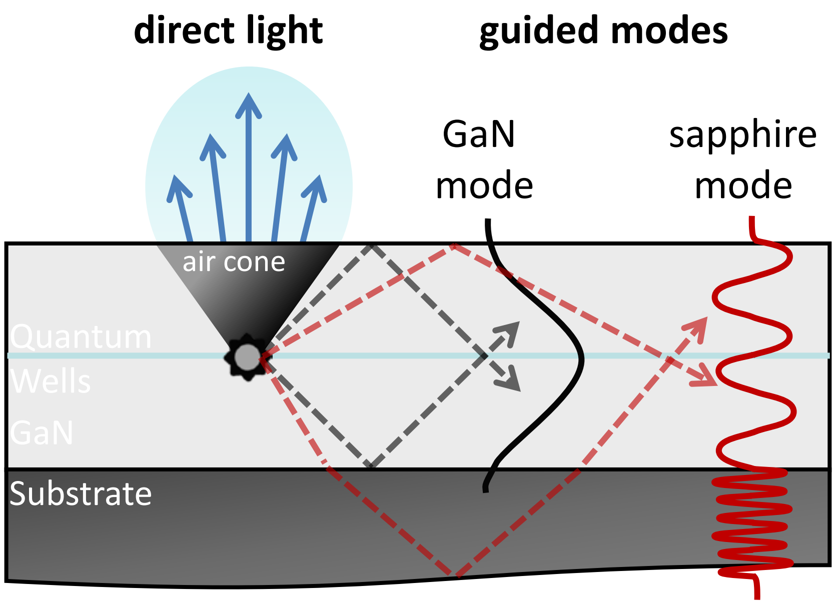
*C-plane data are from non-thin-film flip-chip devices

**All data collected at 22 A/cm^2 or 35 A/cm^2

Light Extraction in LEDs



~ **12%** of emitted light is **extracted**
~ **88%** is **trapped** in the semiconductor as guided modes due to total internal reflection at the semiconductor air or encapsulant interface



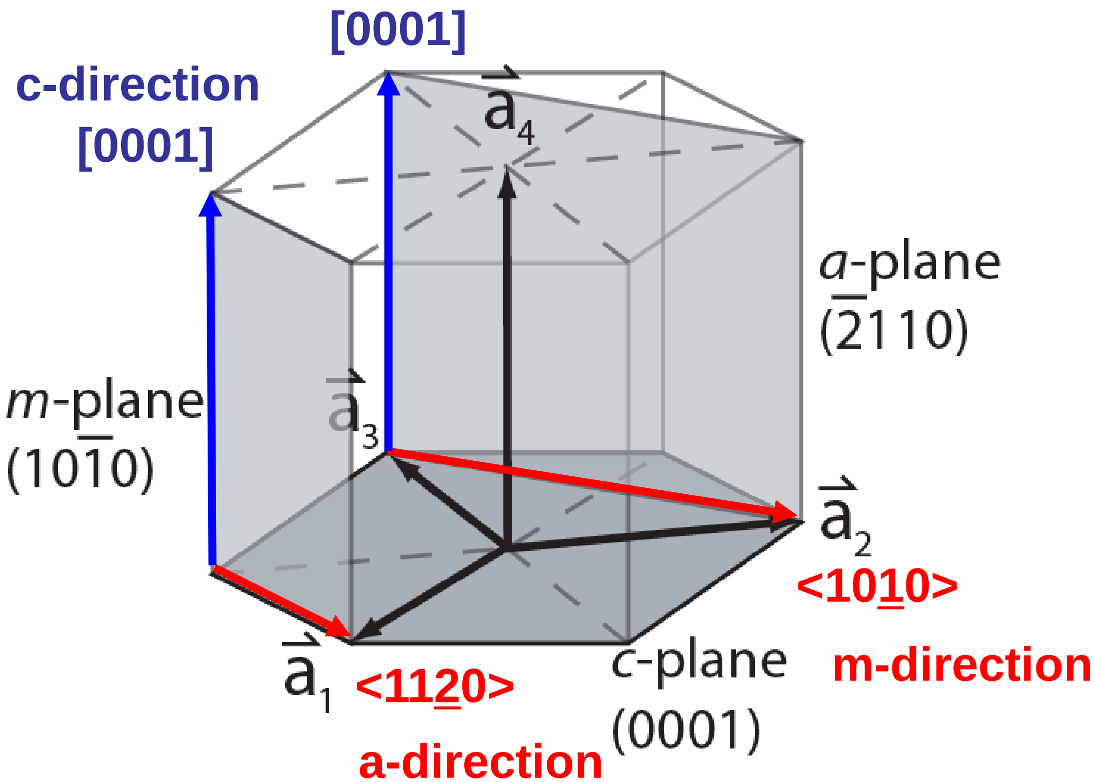
More precisely, in planar structures, light is emitted in **guided modes** either in the nitride layers (66%) or in the substrate (22%)

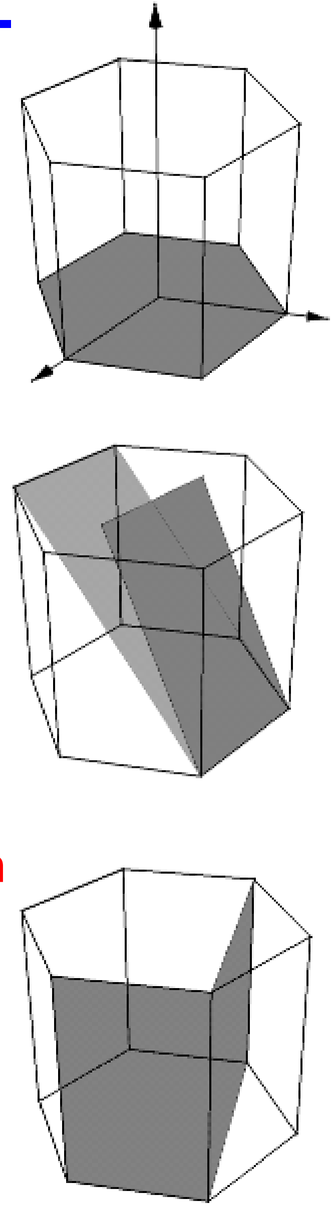
Main light extraction schemes:
*Break propagation of guided modes by using non-planar structures.
*Light extraction is well described by geometrical optics and ray tracing

Solutions to:

Droop, Green Gap, Light Extraction

Wurtzite GaN - Polarization





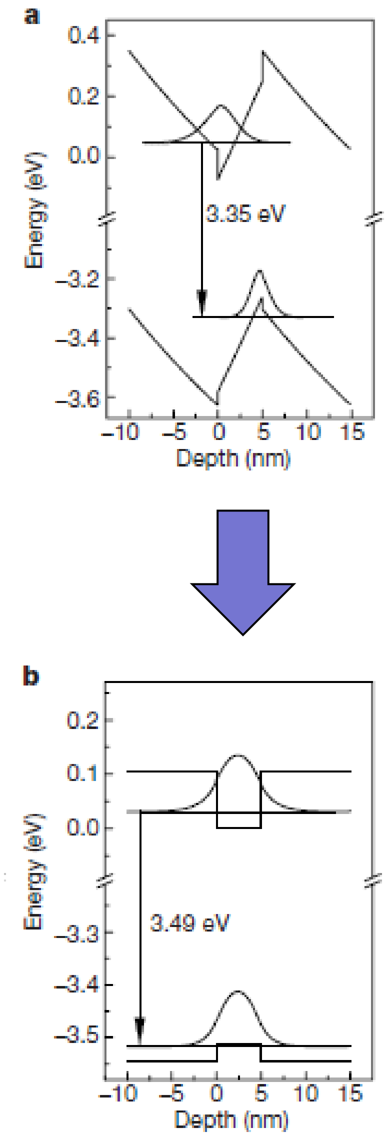


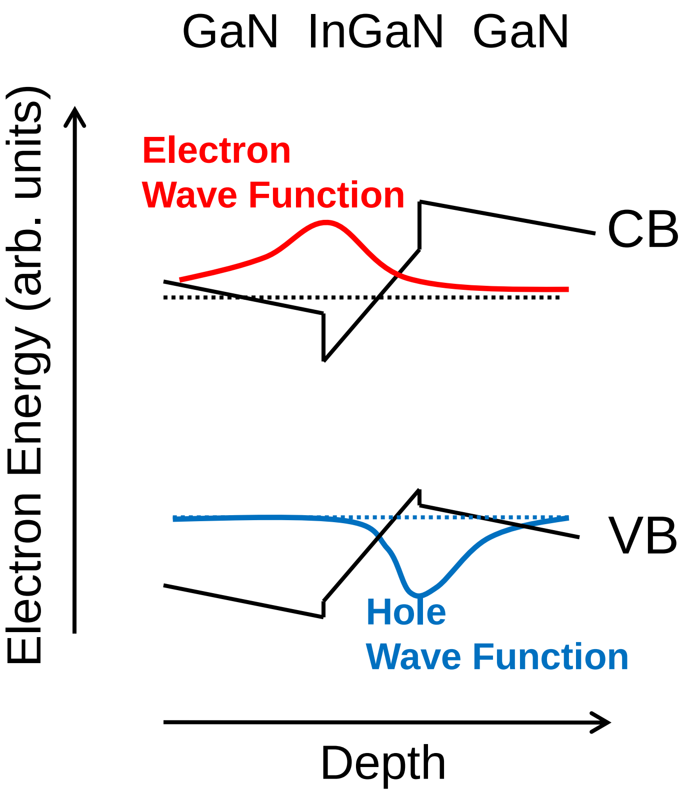
Figure: Mel McLaurin

P. Waltereit et al, Nature 406, L1329 (2000).

QWs on Polar *c*-plane GaN

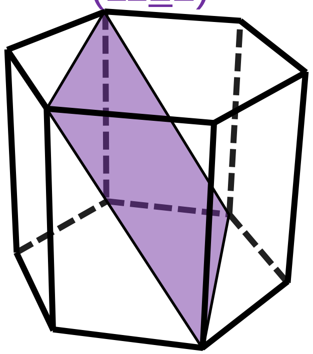
Strained InGaN QWs induce additional piezoelectric polarization

- **Reduced wavefunction overlap**
- **Reduced radiative recombination rate**
- **Reduced transition energy**
- **Carrier transport issues**
- **Emission blue-shifts with current density**
- **QWs are limited in width**

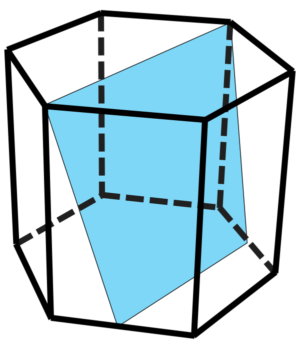


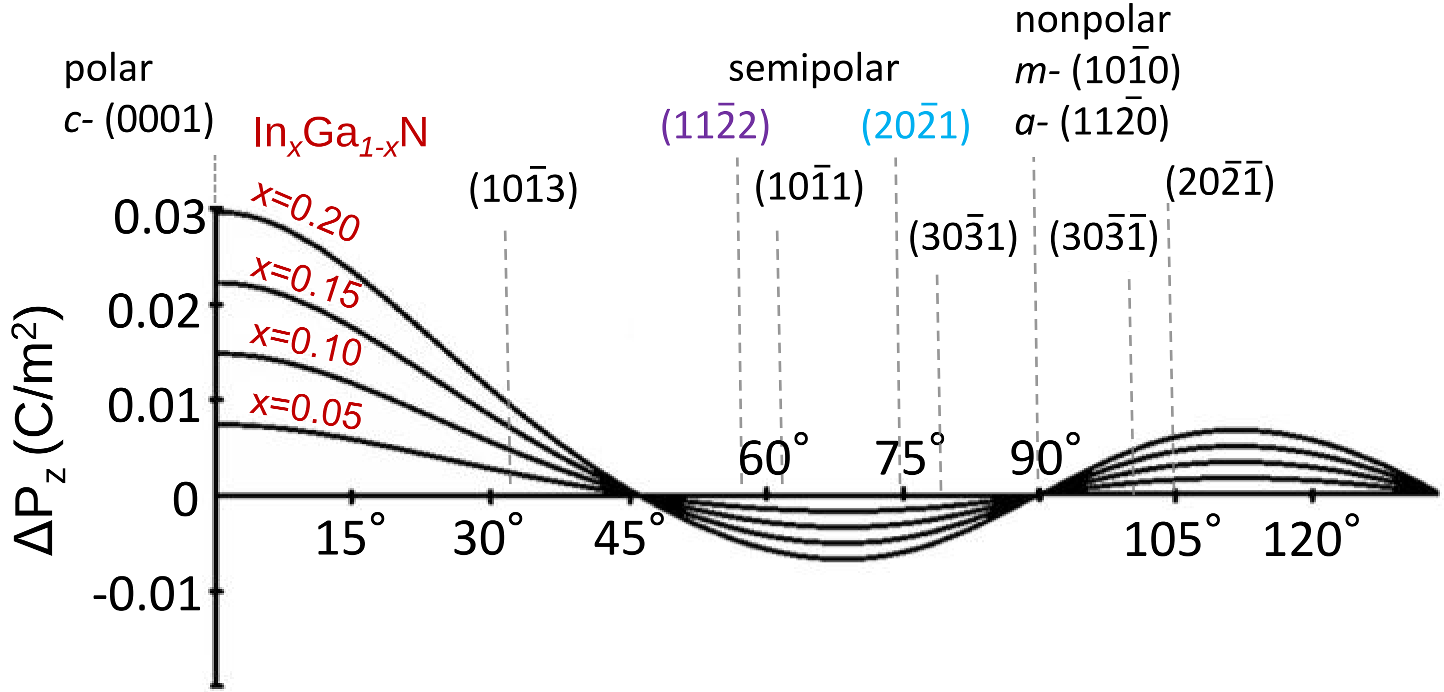
QWs on Semipolar Planes

(11$\bar{2}$2)



(20$\bar{2}$1)

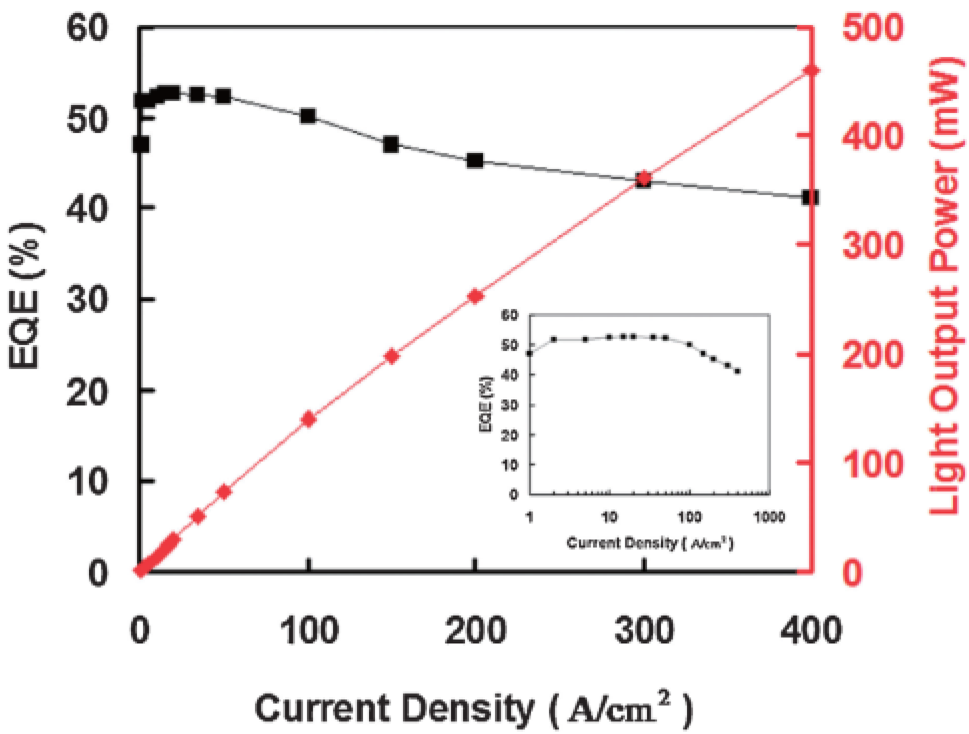




Polarization discontinuity depends on:

- Angle from *c*-axis
- Indium composition

Record Low Droop Blue (20-2-1) LEDs

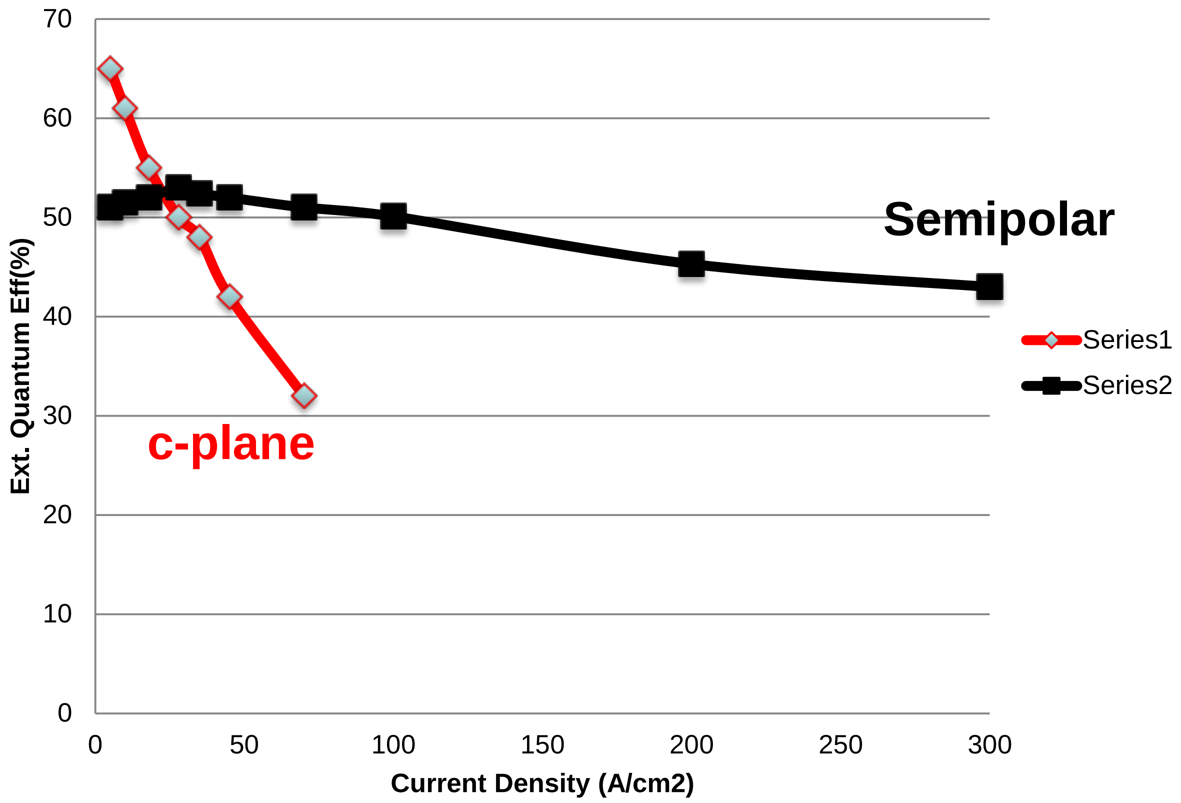


- **SQW: 12 nm**
- 0.1 mm^2 active area
- ITO-based chip
- Transparent LED packaging

$$Droop\ (\%) = \frac{(EQE_{Peak} - EQE)}{EQE_{Peak}}$$

	35 (A/cm^2)	100 (A/cm^2)	200 (A/cm^2)	300 (A/cm^2)	400 (A/cm^2)
EQE (%)	52.4	50.1	45.3	43.0	41.2
Droop (%)	0.7	5.1	14.1	18.4	21.9

Comparison Semipolar (20-2-1) to c-plane



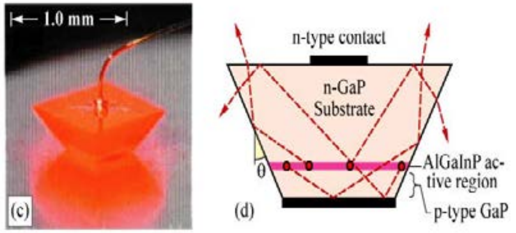
Both Blue 445 nm LEDs on Bulk GaN 0.1 mm^2

Light Extraction – Current Techniques

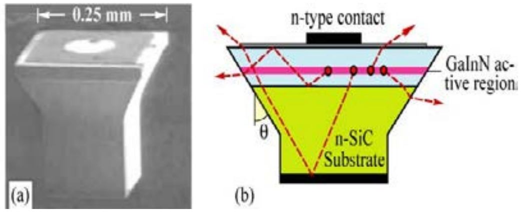
Approaches to $\eta_{extraction}$ ~80%

Chip Shaping

Non-planar process
Long light propagation distances
Requires ultralow substrate loss



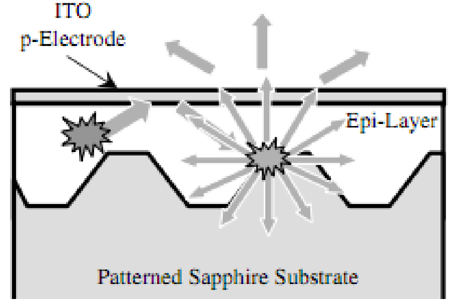
Lumileds



Cree

Patterned Sapphire Substrate

Increased defect density
Poor thermal conductivity

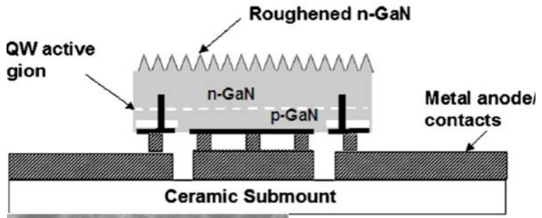


All vendors

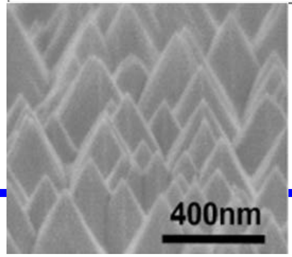
Roughening

Substrate removal
GaN thinning
Silver p-side mirror
Difficult metallurgy

InGaN/GaN Thin-Film Flip-Chip LED



Philips
Cree
Osram



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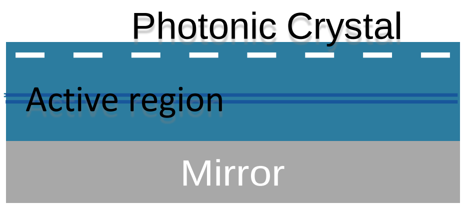
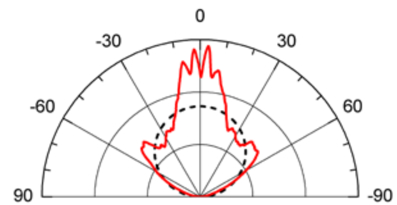
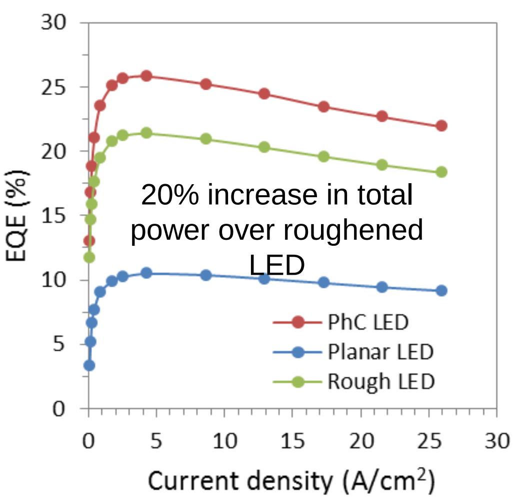
Photonic Crystals: Light Extraction *and* Directionality

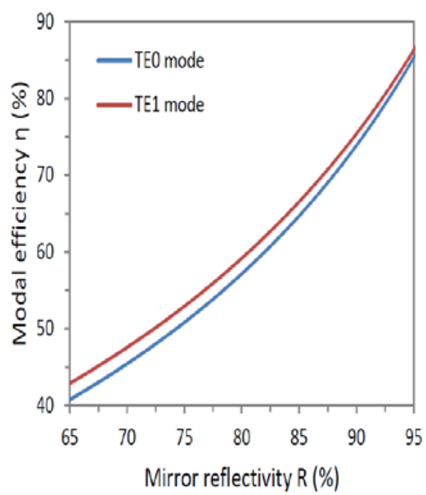
Flip Chip *n*-side PhC LEDs

- high directionality
- strongly limited by p side metal absorption



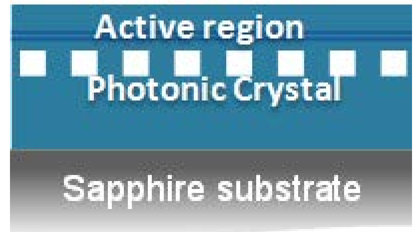


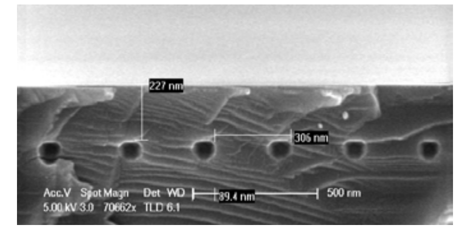


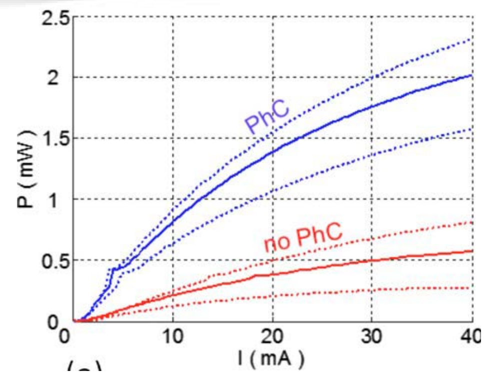


Embedded PhC LEDs

- Novel growth & structures







Extraction efficiency
73% in air
94% in epoxy

All low order modes
$L_{extraction}$ ~ 60-80 μm

Roughness gives Lambertian source
Diectionality by PhC can be useful in lighting

Embedded PhC can better compete with internal loss mechansims

Rangel et al., *Appl. Phys. Lett.* **97**, 061118 (2010)
Rangel et al., *Appl. Phys. Lett.* **98**, 081104 (2011)

Matioli et al., *Appl. Phys. Lett.* **96**, 031108 (2010)

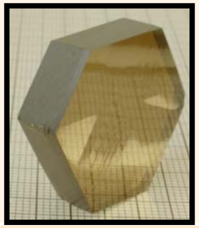
UCSB

Ultimate Solid State Lighting:

Based on bulk GaN

Nonpolar/Semipolar
RGB
Laser-Based SSL

Overview Bulk Growth Results

Technique	Growth Rate	Diameter	Thickness	TD Density	Challenges	Results
HVPE	~ 100 µm/h	2”	5.8 mm	> 10^6 cm^{-3}	Stress/ Curvature Scaling Cost	
Ammono-thermal	**~ 4 µm/h**	**2”**	**> 10 mm**	**< 10^4 cm^{-3}**	**Growth rate Purity**	
HPNSG	**< 1 µm/h**	0.8”	**< 1 mm**	~ 10^2 cm^{-3}	Scaling Growth rate	
Flux	20 µm/h	2”	3 mm	~ 10^5 cm^{-3}	Yield Scaling Cost	

Impact of Bulk GaN

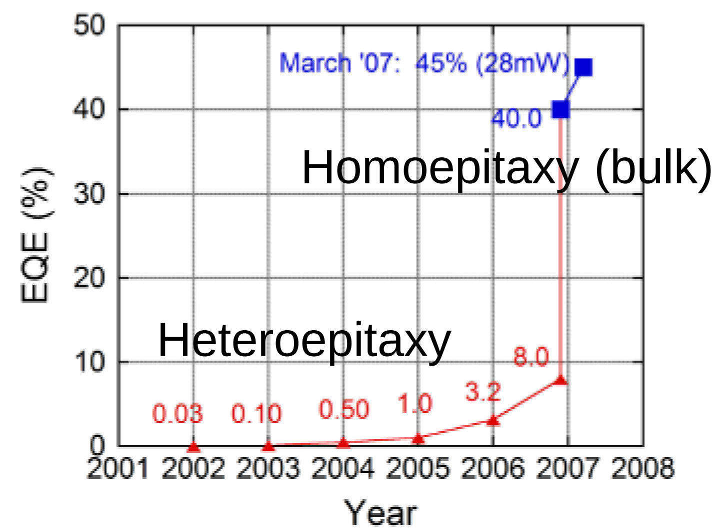
Bulk GaN will enable

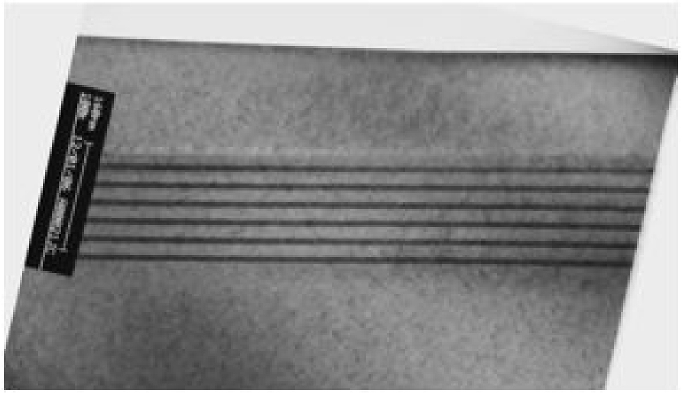
C-plane GaN-based devices
- Improved performance (no TDs)
- Improved yield (No TDs)
- Wafer scaling
  - major origins of bow eliminated

Nonpolar/Semipolar GaN-based devices
- Enabled nonpolar/semipolar devices
- Transition major GaN-based technologies
  - from c-plane to nonpolar/semipolar

Overall analysis:
Ammonothermal shows significant promise for scaling and cost (ultimately <$100/2″ GaN)

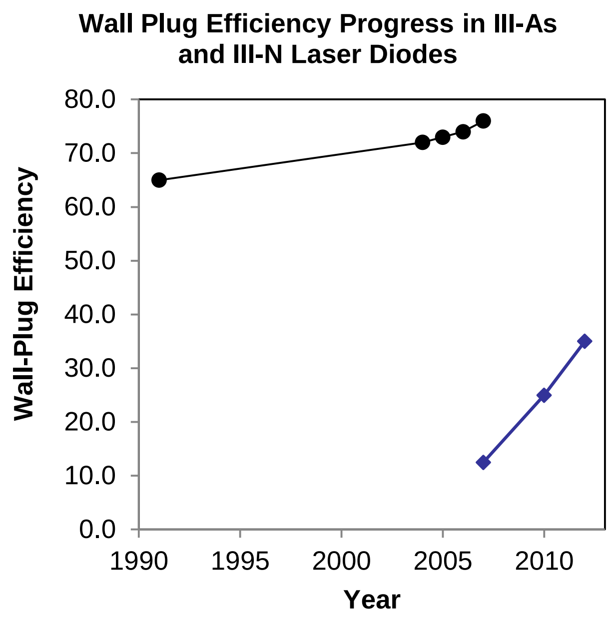
Nonpolar violet LED progress

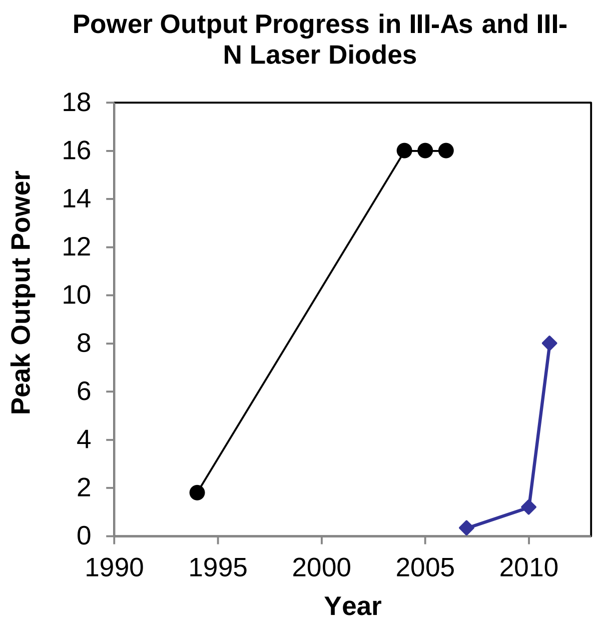




Cross-section TEM:
m-plane GaN LED on bulk GaN

Progress in High Wall Plug Efficiency Laser Diodes





Wall plug efficiency:

Conventional III-V LDs (near IR) >**70%** today; > 10 W power

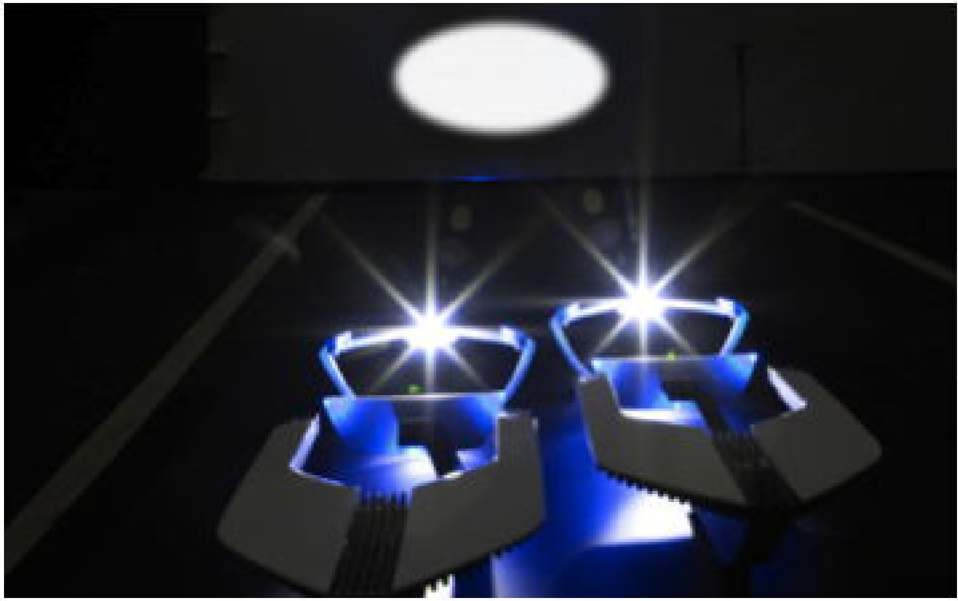
III-N >30% today (blue 440+ nm) >**30%** today; ~5 W power

Blue **LD phosphor converted** white light CRI 90 (363 lm/W max)

35% WPE LD	127 lm/W x 0.75 (phosphor) =	95 lm/W
50% WPE LD	181 lm/W x 0.75 (phosphor) =	135 lm/W
67% WPE LD	243 lm/W x 0.75 (phosphor) =	180 lm/W

Applications of Visible Laser Diodes

Blue laser plus yellow phosphor for directional white light



"Near-parallel beam with a thousand times greater intensity… and half the energy consumption of LED headlights."

Source:
http://www.motortrend.com
http://www.bmwusanews.com

Prospects

Solid State Lighting

Clear path with existing technologies to >**100 lm/W** white:

- Towards $1/klm cost
- Replaces incandescent, halogen, compact fluorescent lights

Need transformative technologies to **200 lm/W** white

- To replace linear fluorescent and HID lamps

Pathway via

- Bulk GaN substrates (enabler)
  - Nonpolar and semipolar GaN for high QE and low droop
  - Laser-based lighting

"**Green gap**" – requires fundamental understanding *and* breakthroughs!

- Solution necessary for RGB-based SSL based on LEDs or lasers

Off-Grid Lighting:
GaN Blue PC LED + Solar Cell + Battery

• 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.

Lighting kit - $38
Solar cell
Battery (5 h charge)
2 x 1000 lm lights

Light up the World Foundation: www.lutw.org

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