PHILIPS

Current State of the Art in High Brightness LEDs

M. George Craford, CTO
American Physical Society
Solid State Lighting Session
March 6, 2007

LUMILEDS
LIGHT FROM SILICON VALLEY

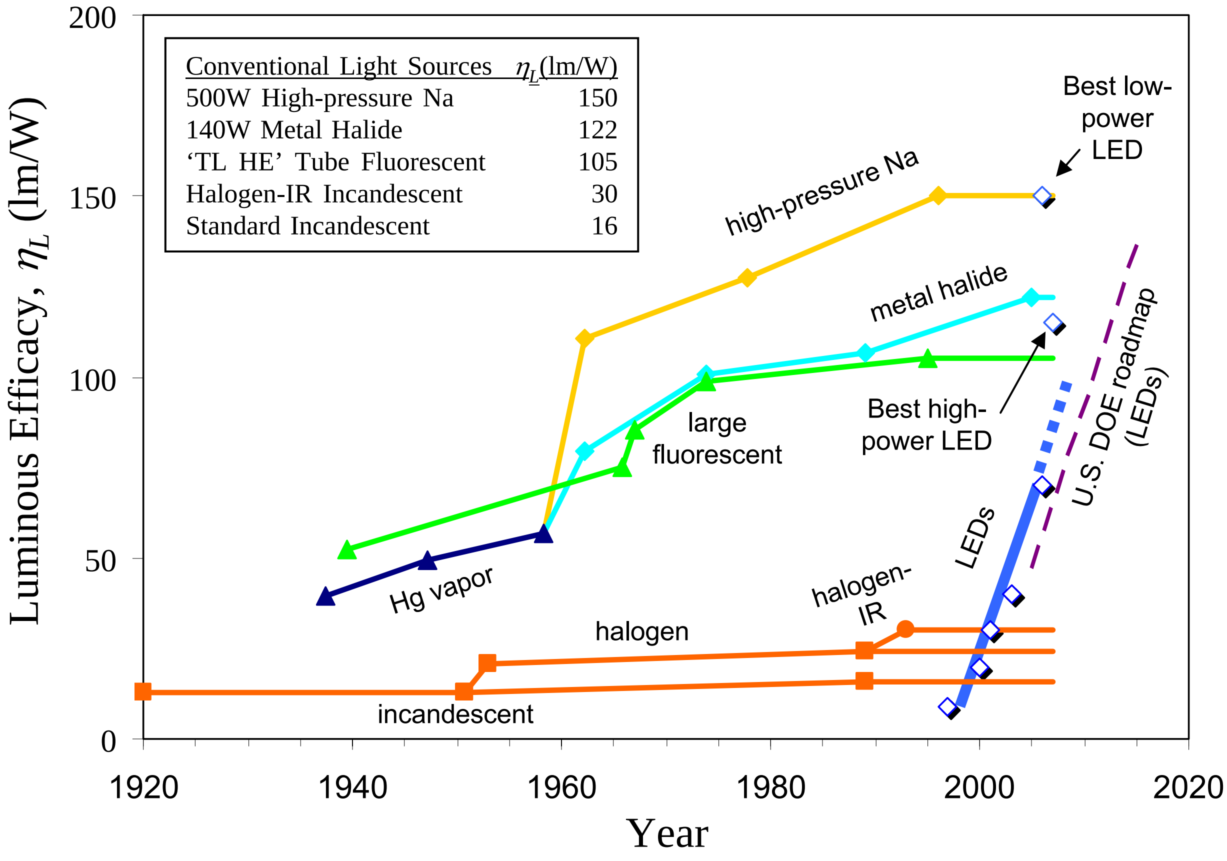
Outline

- Technology Background and Status
- Existing and Emerging Applications
- Challenges and Approaches for General Illumination

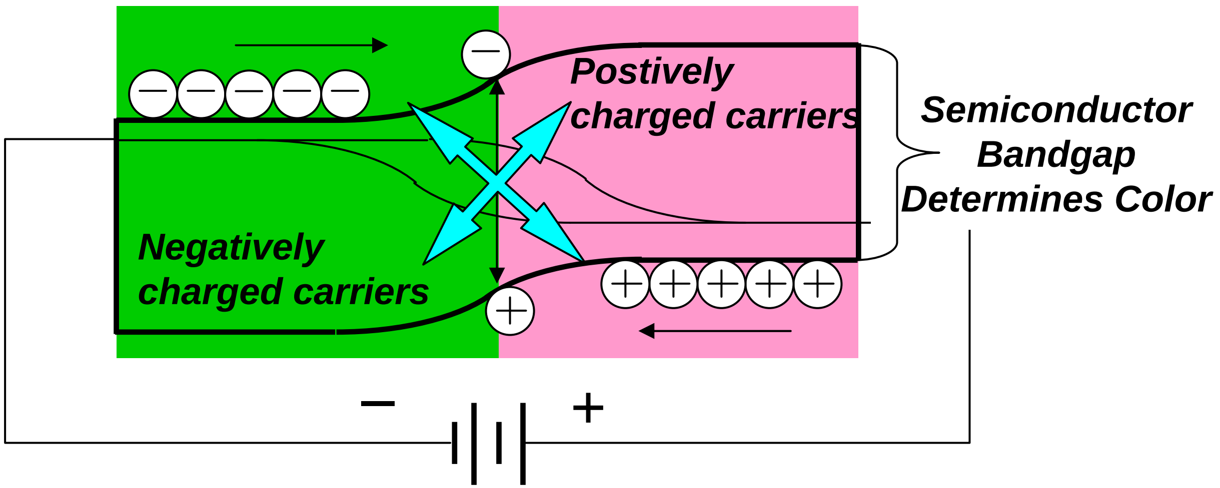
Buckingham Palace, London, England

Lit by Lumileds LEDs

White light source luminous efficacy: conventional vs. LEDs



What is an LED? Why can LEDs be brighter than any other light source?



Colored LEDs:

Red, Yellow - AlInGaP

Blue, Green – InGaN

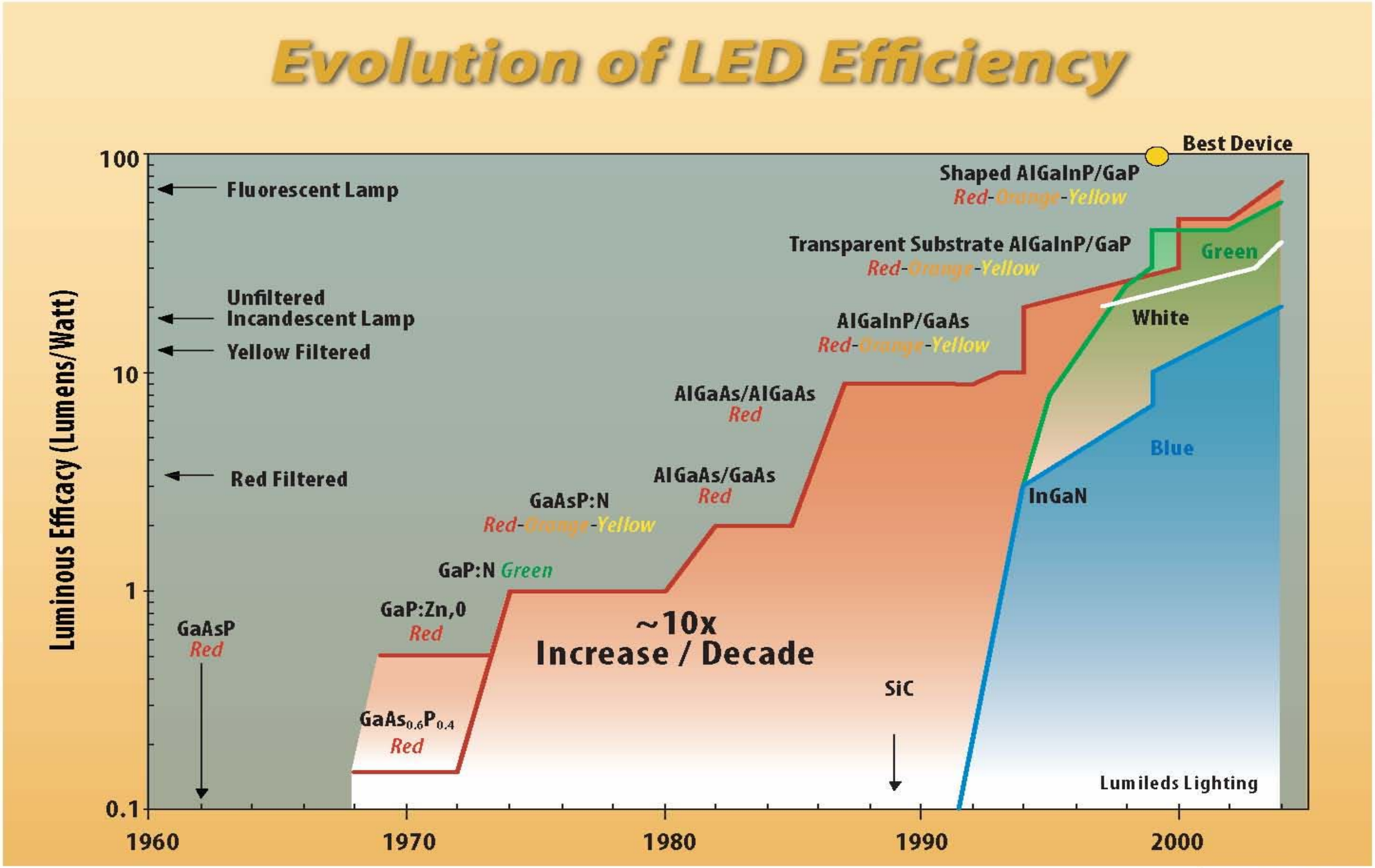
White LEDs:

Red + Green + Blue, or

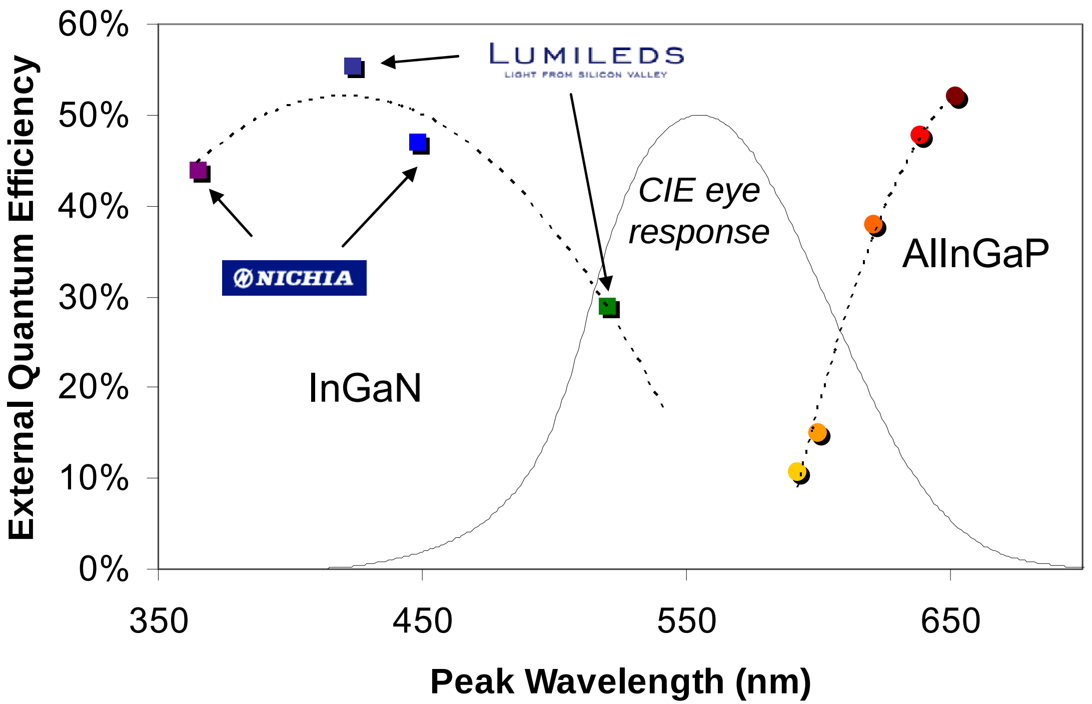
Blue + phosphor

- With applied voltage positive and negative charge carriers recombine
- Energy may be released as light or heat
- Theoretically can be a 100% efficient with unlimited life!
  (compared to incandescent which is 5% efficient, 2000 hour life)
- Commercial LEDs can be expected to reach 50% efficiency and possibly more

Evolution of LED Efficiency



State-of-Art: 350mA High-Power LEDs



III-P:
- Fundamental band-structure limitations

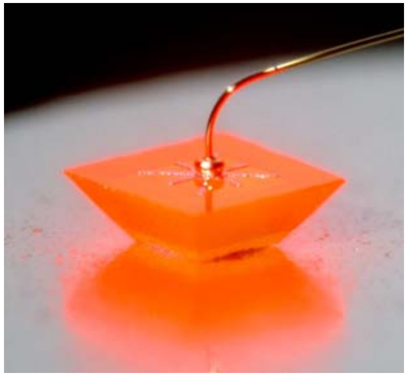
III-N:
- IQE (~450 nm) ~55 %
- IQE (~520 nm) ~20 %

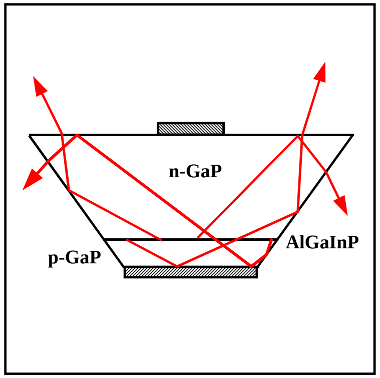
(1): Nichia Chemical Co., IWN 2004
Remainder data: Philips Lumileds (70 A/cm[2])

- External Quantum Efficiency: EQE = Internal QE × Extraction Efficiency
  $EQE = P_{optical} / (E_{ph} \times I_f)$
- Power Conversion/Wallplug Efficiency: PCE or WPE = $P_{optical} / (V_f \times I_f)$
- Luminous Efficacy (lumens/Watt): LE = PCE × V (λ)

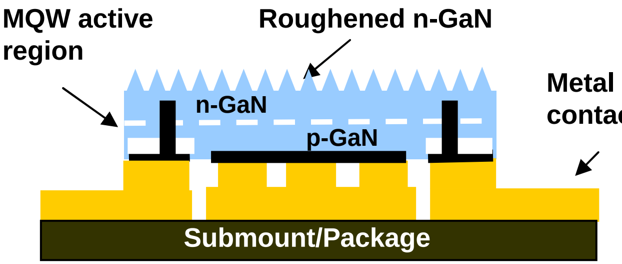
Light Extraction From LEDs

Lumileds AlGaInP/GaP Truncated-Inverted-Pyramid LED

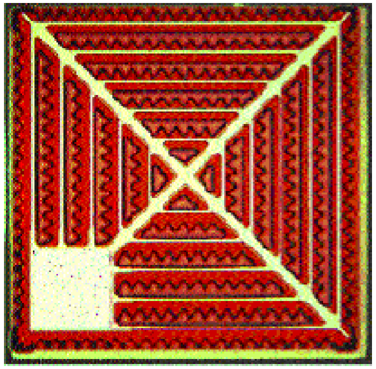


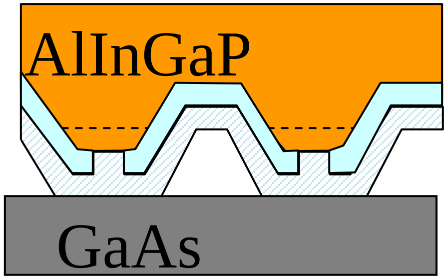


Lumileds Thin Film Flip Chip (TFFC) Structure

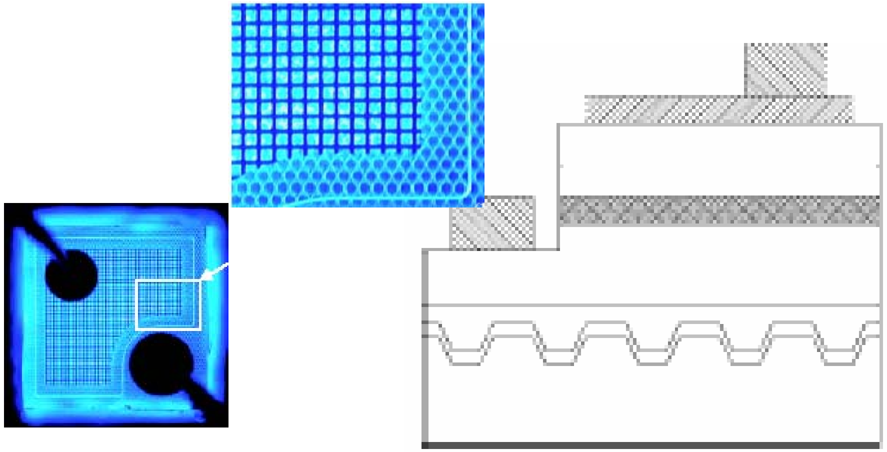


OSRAM AlGaInP Micro-mirror LED

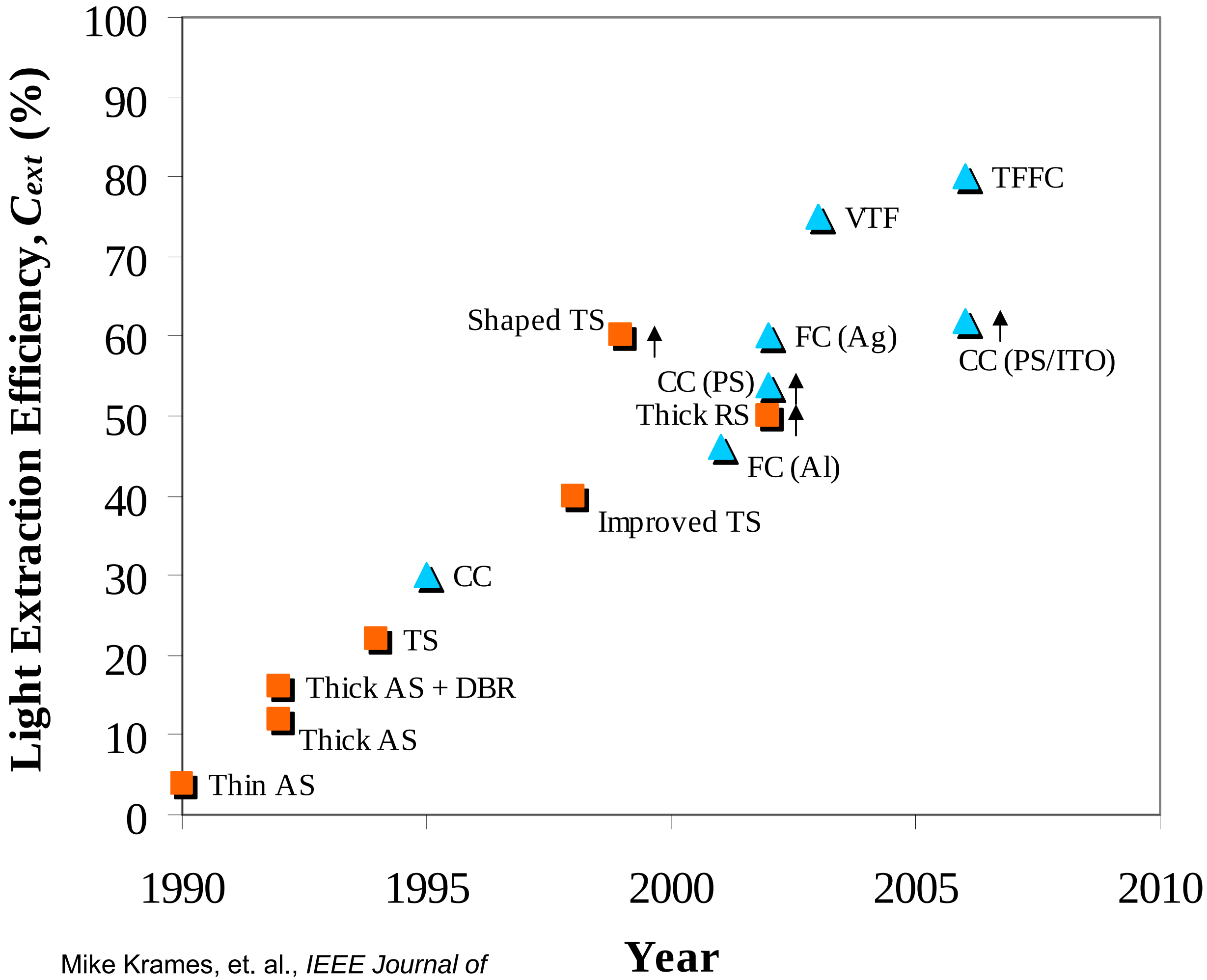




Nichia AlInGaN patterned substrate and mesh electrode LED



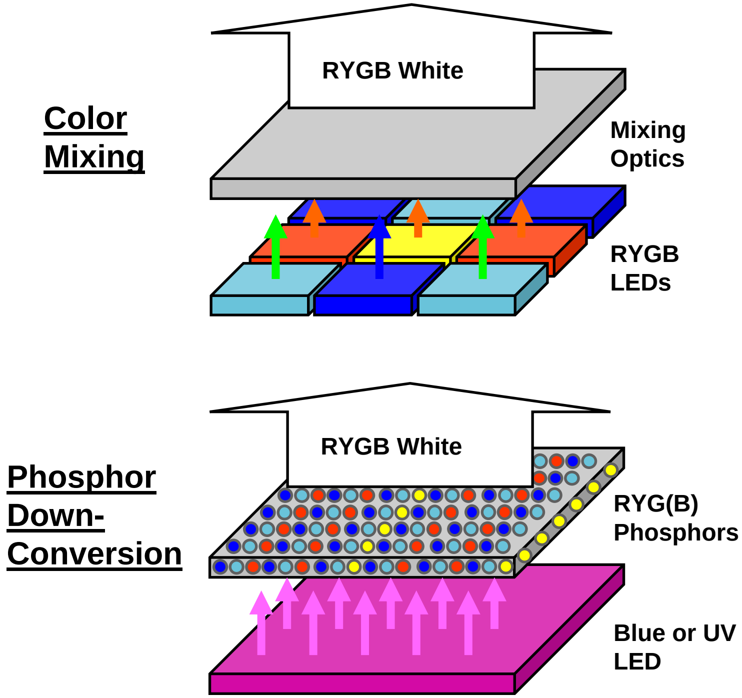
Evolution of light extraction efficiency for AlGaInP and InGaN-GaN LEDs

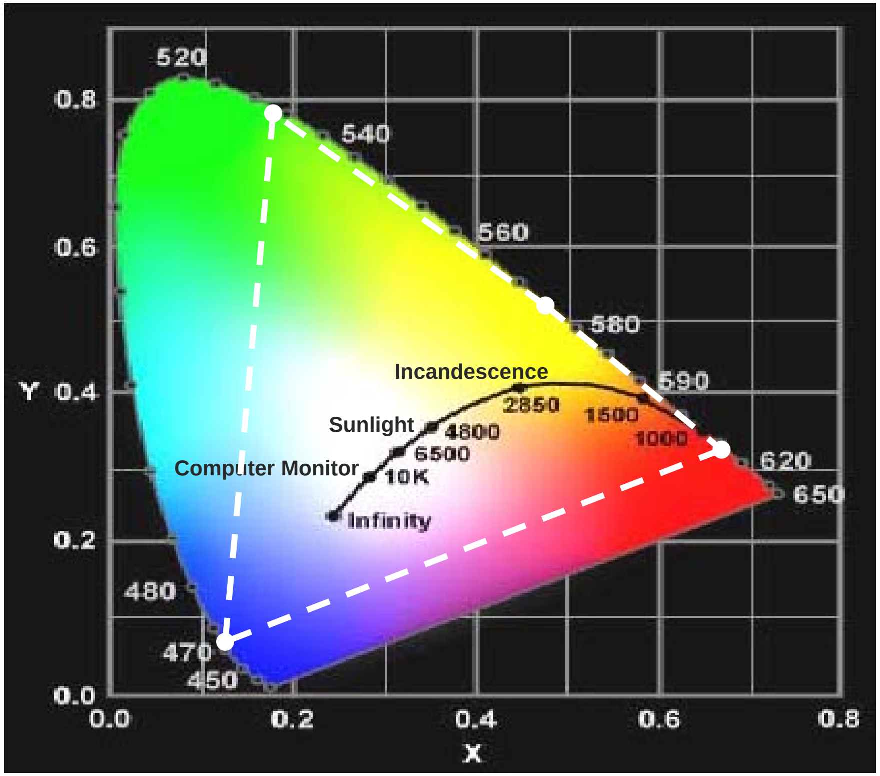


Mike Krames, et. al., *IEEE Journal of Display Technology*, March 2007

- In the past extraction efficiency improvements have been substantial (>10x)
- C_{ext} is approaching a practical limit
- In the future there is more opportunity for improvement in IQE, especially in the green

Making White

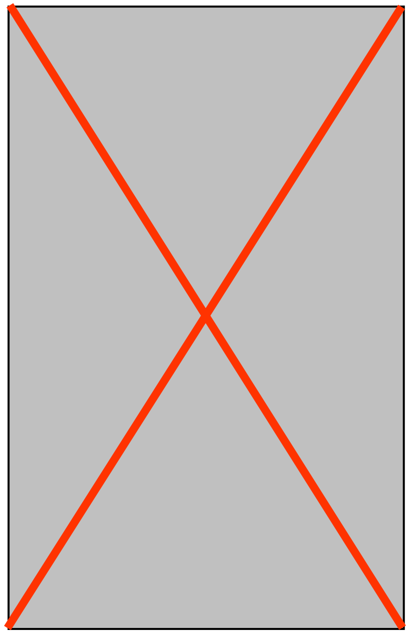




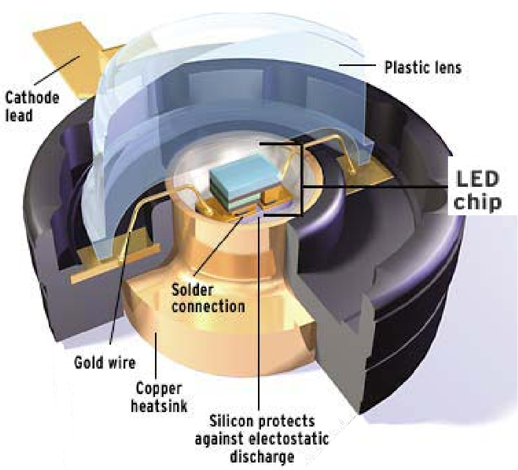
Images courtesy Jeff Tsao (Sandia National Labs)

- Issues:
- Phosphor conversion
  - Quantum deficit, optical losses, new materials issues
- Color mixing
  - Optical losses, color uniformity, color control circuits

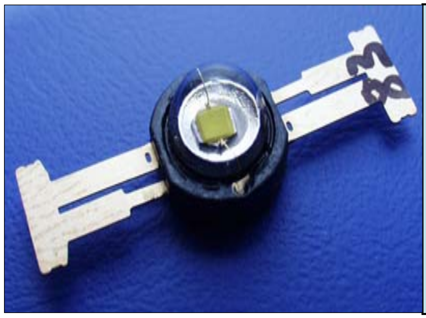
Trend to Higher Power Packages



LUXEON® Package



LUXEON® I / III

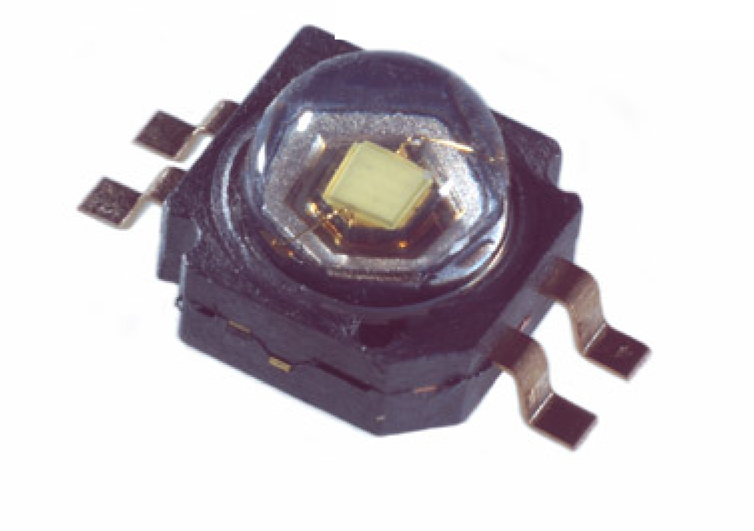


First high-power LED on the market (1998)
- Chip ≥ 1 mm^2
- R_{th}` ~ 15 K/W
- P_{in} = 1-5 W

LUXEON® K2

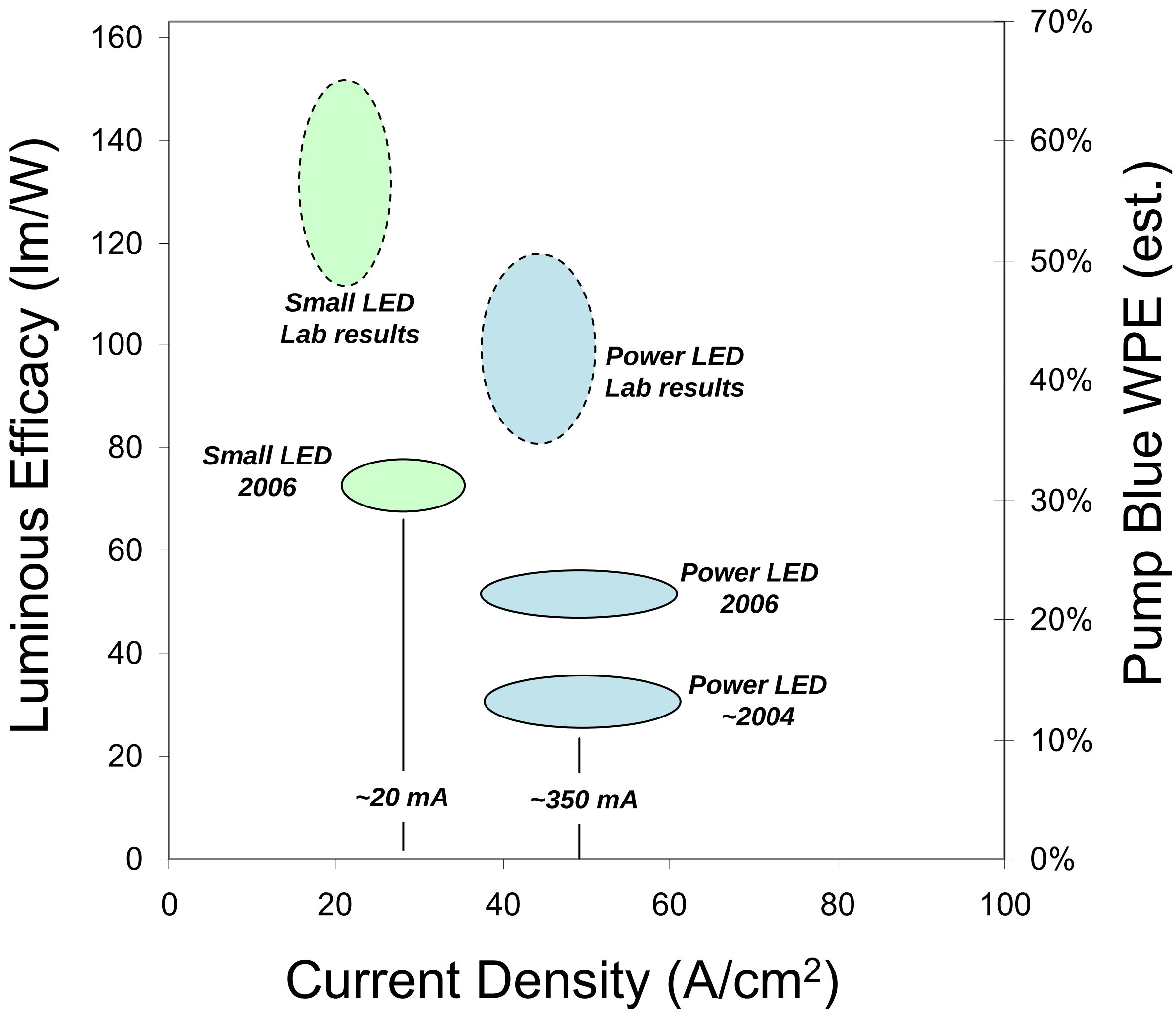
- Lower thermal resistance – 9 K/W
- Higher operating temperature – 185°C
- Higher drive currents – up to 1.5 A
- Higher flux – up to 140 lm in white

- Surface mountable, Pb-free
- Superior moisture tolerance JDEC 2a)



White LED Performance

"Cool" CCT ~ 5000-7000K



- Small 5mm LEDs
  - Lower current density
  - Lower forward voltage
- Power LEDs
  - More lumens/package
  - Lower cost per lumen

High-power LED Applications: Single-color

- Many applications benefit from LED advantages
  - Low power consumption
  - Ruggedness
  - Long life
  - Small source size
  - Color purity
  - …

- Key applications
  - Traffic signals
  - Automotive

- Thus far, >50 % of all traffic signals in the US have been replaced with LED versions*
- Energy and maintenance savings are key drivers

*Strategies Unlimited

Energy savings: 89 %
Maintenance rate: 5 %
(vs incandescent lamp)

- 60 M vehicles produced annually
- ~50 % of CHMSL and ~5-10 % of RCL are LED-based today
- Market adoption driven by styling, safety, and fuel savings

Mercury Montego

Honda Accord

LEDs will dominate

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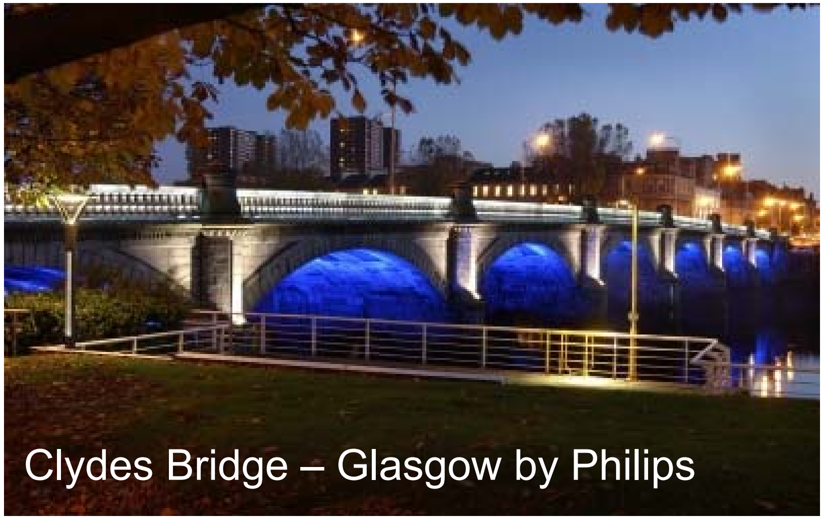
LIGHT FROM SILICON VALLEY

LUXEON Applications


Clydes Bridge – Glasgow by Philips


Hard Rock Hotel –
by Color Kinetics


Shanghai Grand Prix –
by SpaceCannon


Shanghai Grand Prix –
by SpaceCannon

High-power LED Applications: RGB White

- Illumination
- LCD Backlighting
- Projection

- LUXEON I and LUXEON III
- Replicates day-light without harmful ultra-violet or infra-red radiation
- Exact color rendition


Mona Lisa Lighting by Fraen Corporation

SONY Qualia 005

- Triluminos™ LED backlight for LCD panel
- Ultra-high color gamut (105 % NTSC)
- LEDs eliminate motion artifact
- Mercury free
- Long life

Pocket Projectors

- Flux: 12 – 100 lm
- Power: 10 – 25 W
- Weight: 1 – 1.5 lb
- Battery life: 2.5 h

Toshiba TDP-FF1A

Mitsubishi PK-10

Samsung SP-P300M

High-power LED Applications: PC White

- Portable lighting
- Mobile phone camera flash
- Illumination
- Automotive forward lighting

- LUXEON V
- 2 – 80 variable lumens
- 1 - 40 variable hours
- Non imaging optics

Surefire DEF 1

- Functional flash (<~3m)
- LUXEON Flash 
- LUXEON Module 

Casino Breda, Netherlands by Bocom

Daytime Running Light (DRL)

- Multiple LEDs per DRL
- 100°C ambient temperature

S8 S6

LUXEON®-Based Forward Lighting Concepts

THE WALL STREET JOURNAL MAY 4, 1971

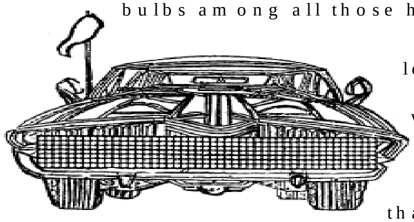
Will anyone living, live to see our little light burn out?

After 100 years of constant use, it may lose only half its brightness.

That's because we don't use a bulb, a filament or a vacuum.

We use a tiny crystal chip called a light emitting diode. It works something like a transistor, but let's not get into all that.

Our diodes are already in use on computer panels, freeing the man who used to look for burned-out bulbs among all those hundreds of winking lights.



That's a good market. But let's look at markets to come.

How about a flat head-light as wide as your car, to evenly light the road?

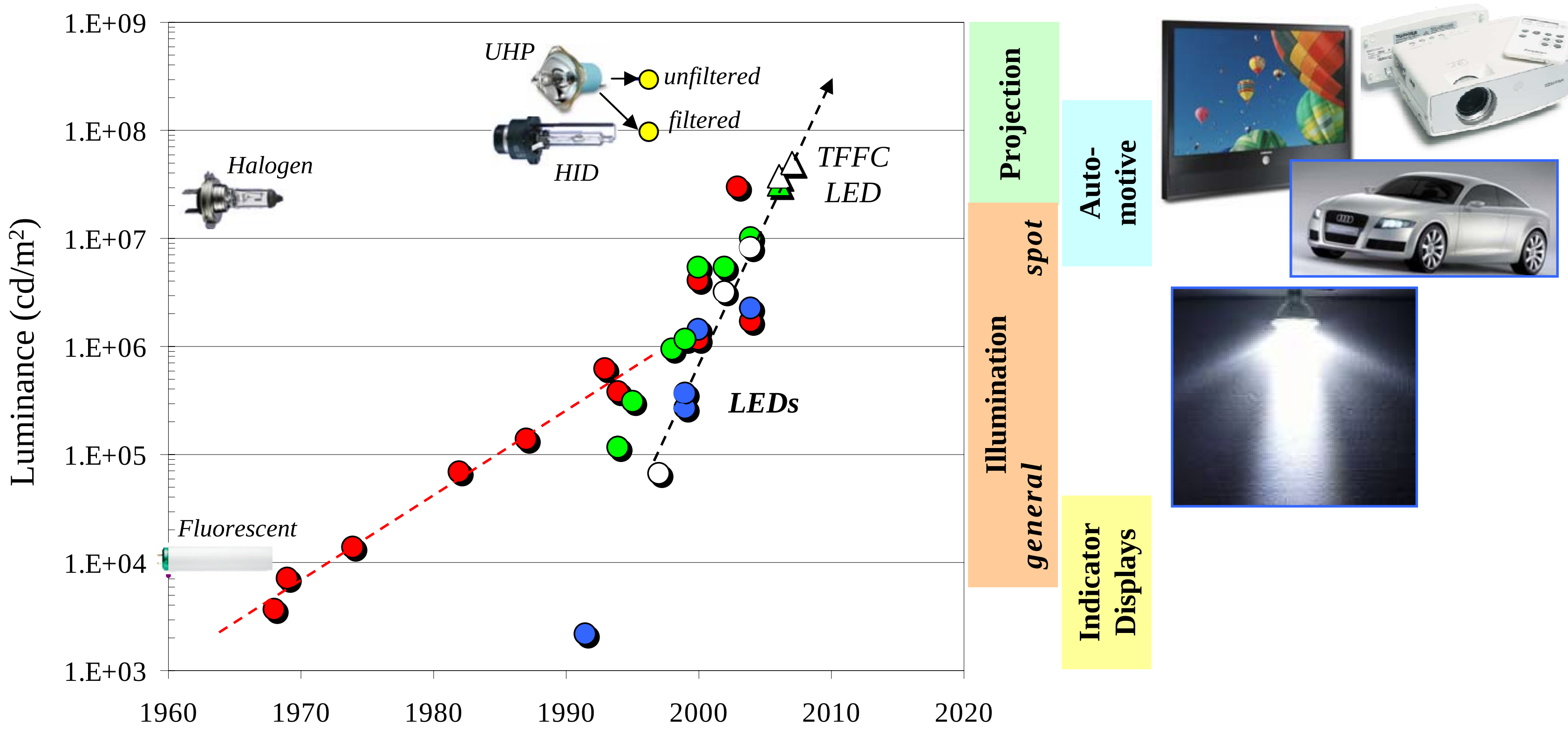
Or an inch-deep color TV set?

Or a wrist watch without a dial, that shows the time in numbers at the instant you push a button?

That's part of the future we see in our crystal chips. And just a small part of the future we see in **Monsanto: the science company.**

Audi Nuvolari Concept

InGaN Devices: Evolution of LED source brightness

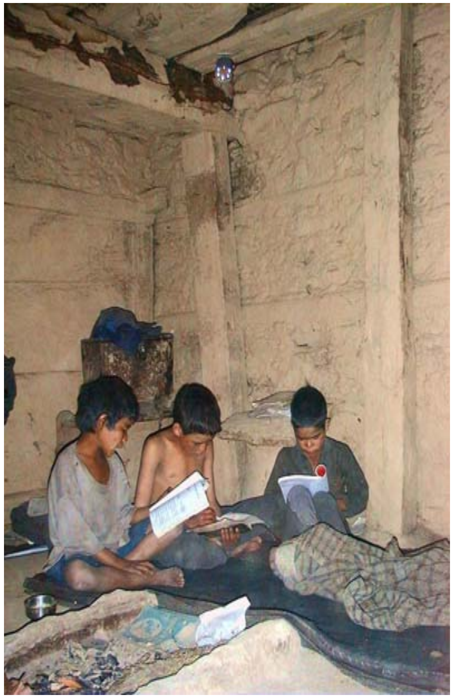


- 50 M cd/m^2 (“Meganits”) measured at 1 A drive current

LUXEON Applications – Interior Lighting

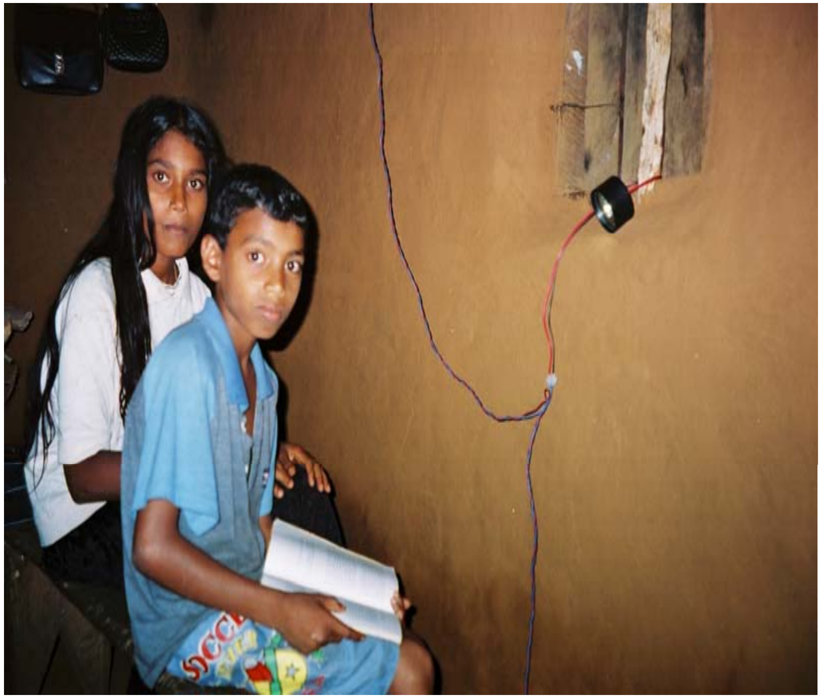
Gimla Yacht – lighting by LightGraphix - fit for life, high performance

LED General Illumination for Off Grid Homes



Nepal 2000*

India 2001*



Sri Lanka 2003*

*** Photos Courtesy of Light Up the World and PICO Power**

Why are LEDs Not Yet Widely Used for General Illumination?

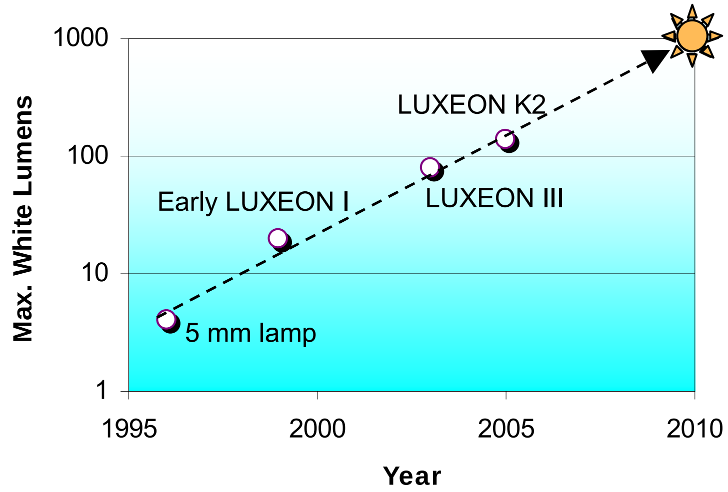
- Cost has been too high
- Efficiency has been too low
- White "color" needs to be warmer and better controlled
- Engineering challenges: thermal, optical, electrical

Efficiency Requirement for PC White

- Single-emitter Flux

  → **1000 lm desirable**

  – same as 60 W light bulb
  – today's LEDs: 30 – 160 lm



- Approach I: Cost of Ownership (COO) Analysis – 1000 lm source

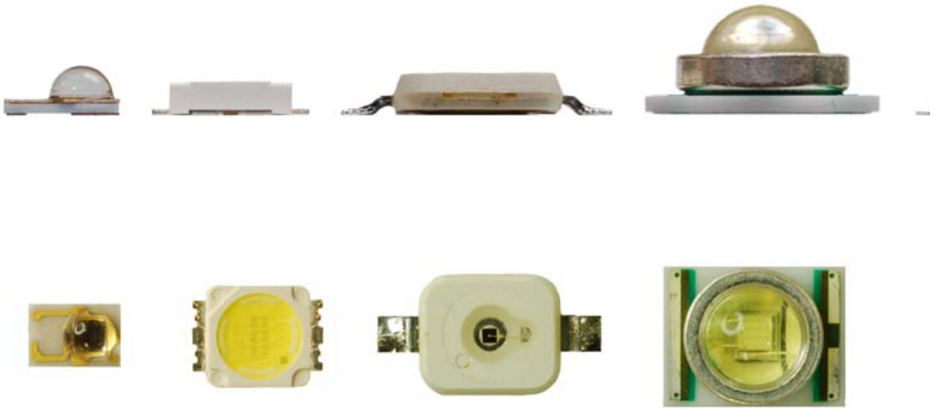
	Input Power	Source cost	Energy cost/yr	COO (1 yr)	COO (5yrs)
1 x 60 W incandescent	60 W	\$ <1	\$ 48	\$ 48	\$ 240
7 x LUXEON K2 emitters	40 W	\$ 18	\$32	\$ 50	\$ 178
1 x 150 lm/W LED	6.7 W	\$< 2	\$5.30	\$ 7	\$ 28

at \$0.10 per kWh

→ **PC White LED: ~150 lm/W**

Smaller high-power packaging

Reducing the cost of light



Continued efforts to develop new package technologies that enable lighting possibilities — improved color mixing and diffusing, smaller luminaire design — and drive the cost per lumen lower. (Coming this quarter)

How Achievable is 150 lm/W ?

	PC White	
	Today*	**Future**
C_{ext} (%)	~80	**~90**
IQE (%)	~55	**~90**
EQE (%)	~45	**~80**
V_f (V)	~3.3	**~2.9**
WPE (%)	~35	**~75**
LE (lm/W)	~70	**~150**

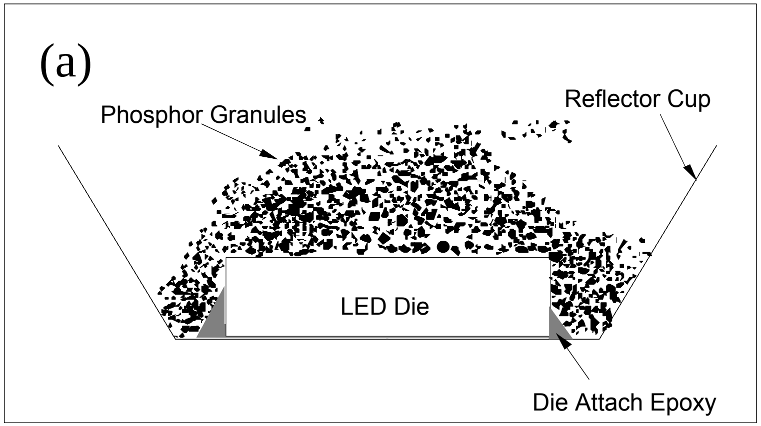
* High performance commercial "cool white" LED.

1mm² chip driven at 350mA.

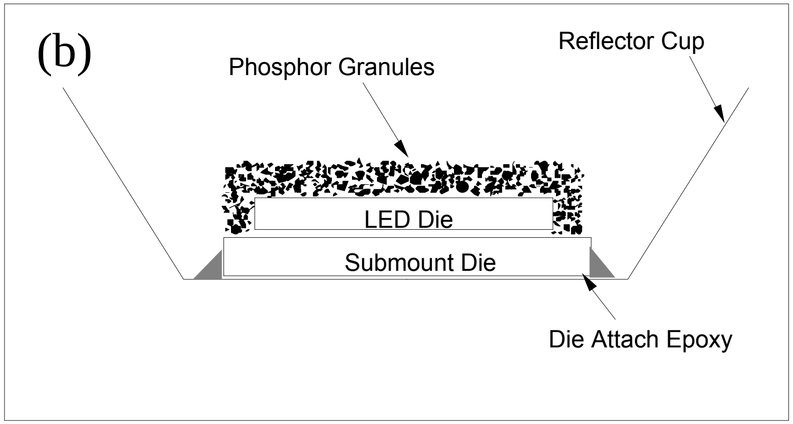
- IQE must increase by >1.5X
- This table assumes a phosphor conversion on 200 lumens/optical Watt for "cool" white (CCT >5000).
- For "warm" white (CCT 3000 – 4000) the conversion is significantly lower and requires development. This is an issue for illumination.
- To achieve 1000 lumen source drive current must be ~2A which reduces luminous efficacy (LE).

White Light Quality and Color Temperature

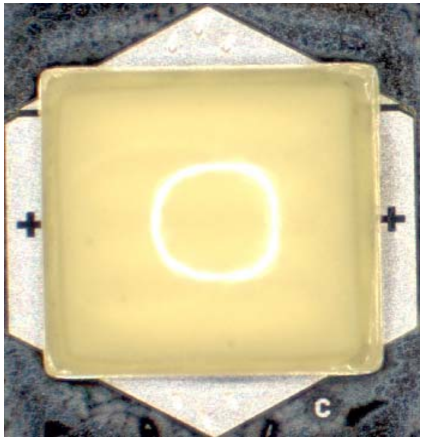
Conventional



LUXEON (Conformal Coating)



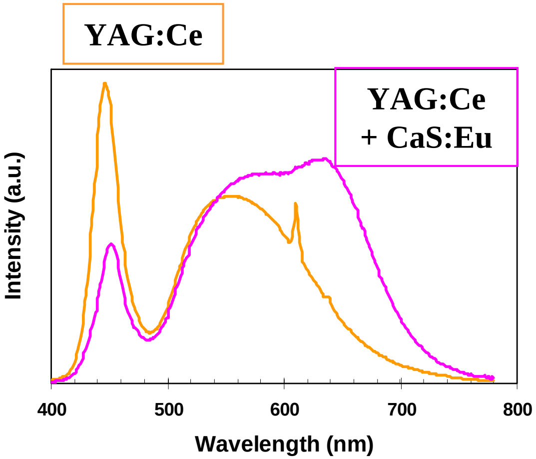
Free standing white chip



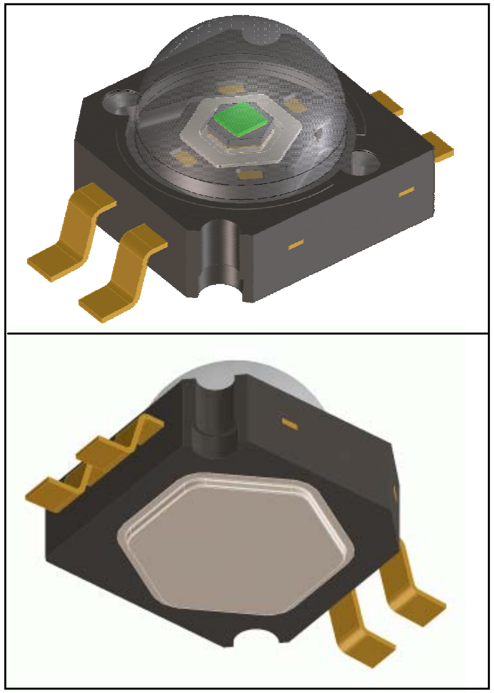
Improved Uniformity

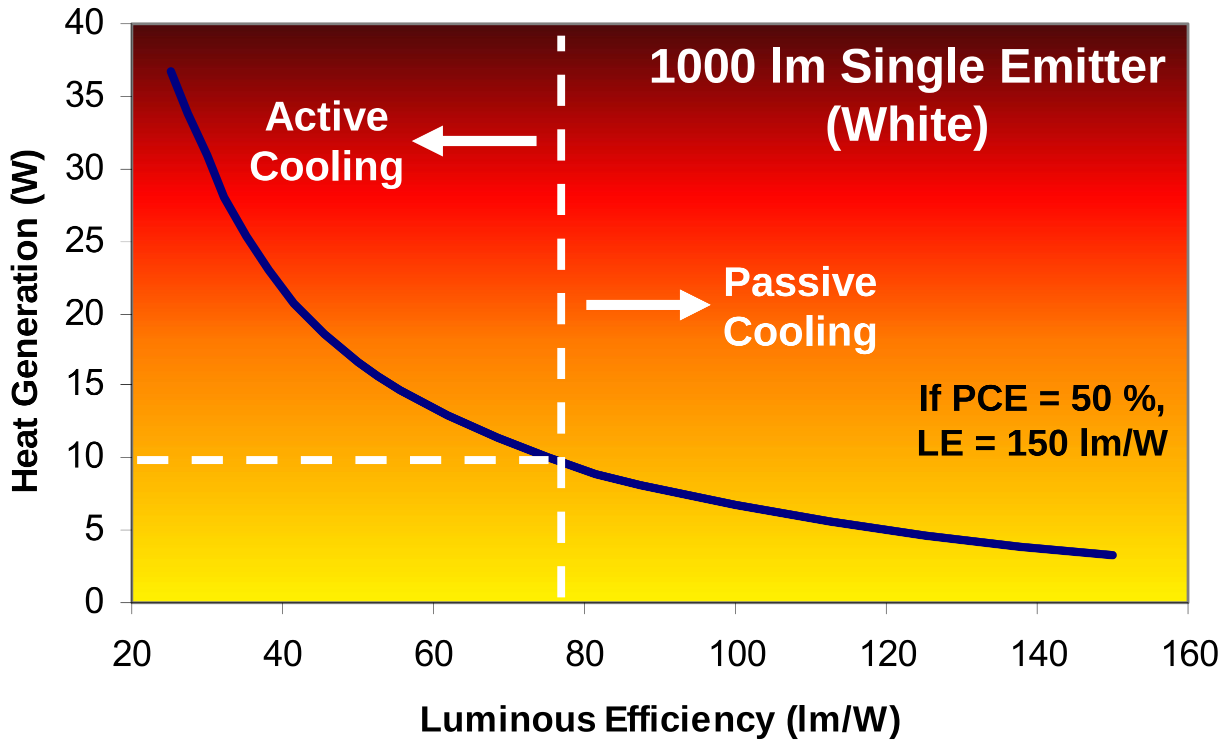
	YAG:Ce	YAG:Ce + CaS:Eu
CRI:	**~75**	**~90**
CCT:	**~6000**	**~3200K**
***Conv. Eff.*:**	**~200**	**~160 lm/W_{opt}**

- Excellent match to blackbody radiation.
- Need higher performance “warm” white with good CRI for general illumination.



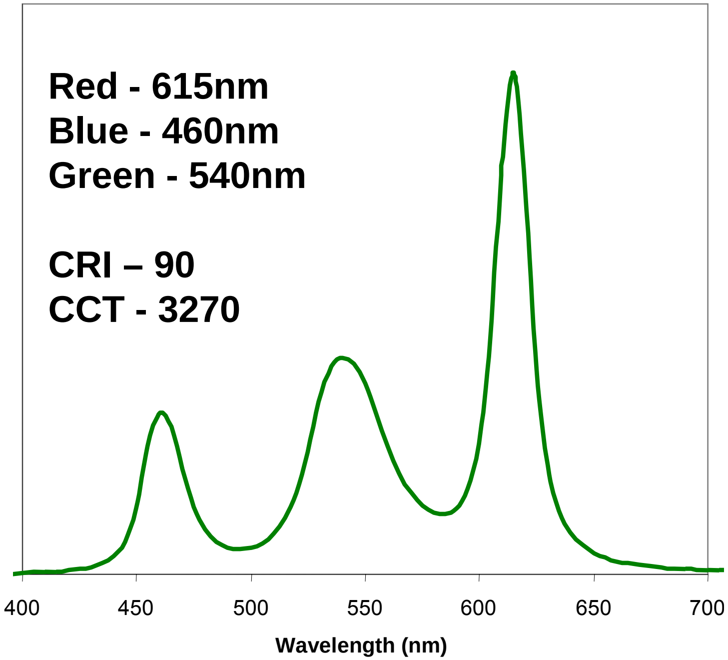
Heat Removal

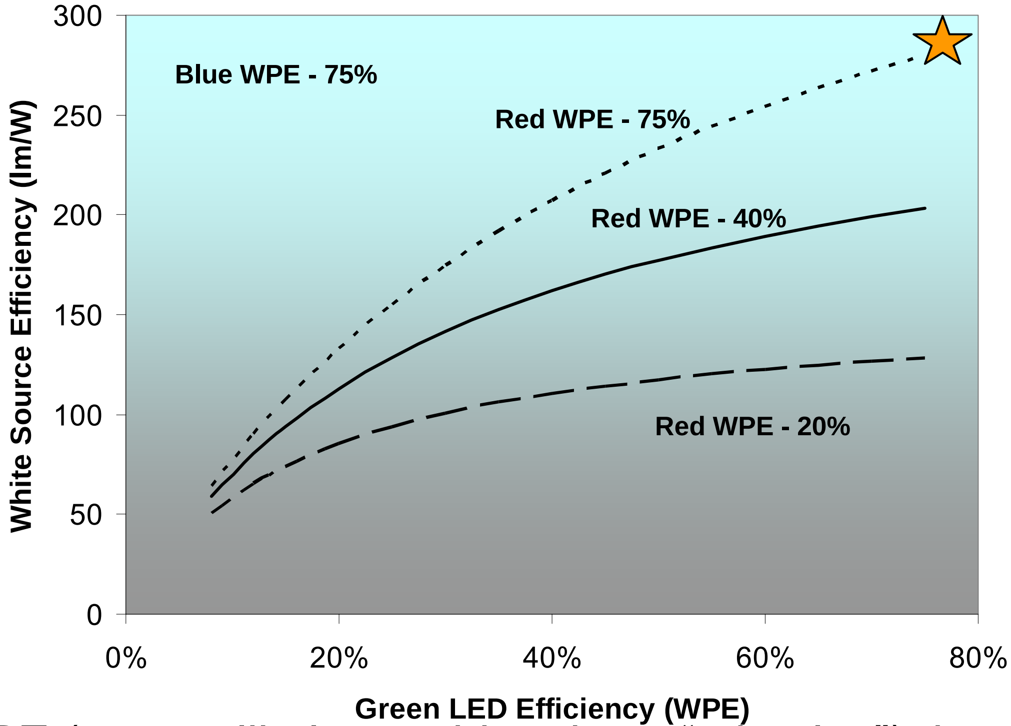




- LEDs pass all heat back to heat-sink and fixture.
- Today's efficiency: Thermal management remains an issue and cost driver.
- Future efficiency: Heat management will be straightforward.

Red, Green, Blue Color Mixing for Warm White Illumination





•If nitride RGB all reach ≥ 75% WPE (very unlikely requiring three “miracles”) then the source efficacy would be ~280 lm/W before color mixing losses (possibly 25% → 210 lm/W)

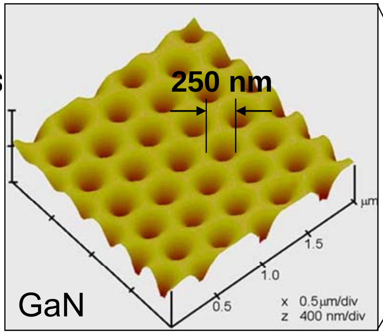
•If RGB all reach >40% WPE (much more reasonable to expect) then ~150 lm/W source would be achieved which would be color tuneable

•Green is the key for enabling color tuneable white illumination to occur

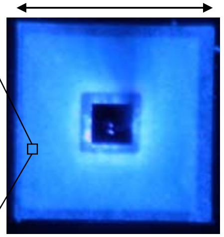
Photonic Crystal LEDs

- Further increase of C_{ext}
  - Extraction of waveguided light
  - Potential increase of IQE
- Directionality of emitted light
  - Directed emission without lenses
  - Increased surface brightness
  - Important for projection applications

Sandia National Laboratories

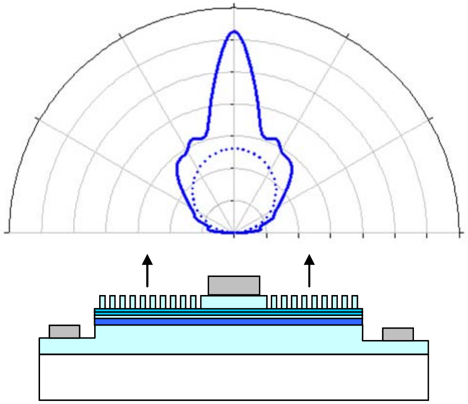


Patterning by e-beam lithography (Sandia)

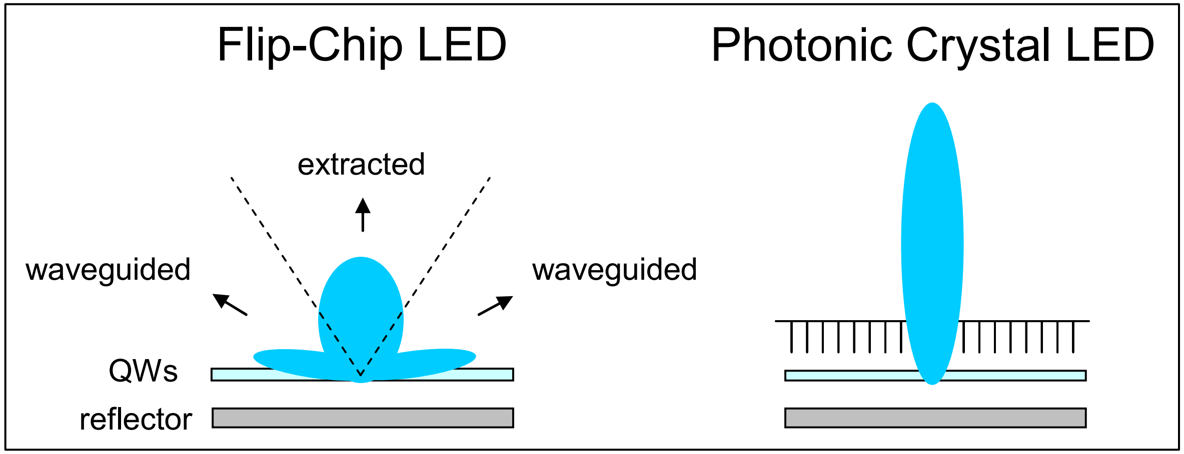


Top-view of a Photonic Crystal InGaN LED

Wierer et. al., *Appl. Phys. Lett*. **84**, 3885 (2004)



Light intensity vs. angle. ~1.5x total flux compared to planar device.



Recent Laboratory Result

On Jan. 23, 2007 Philips Lumileds Lighting Company announced a new achievement in white (CCT = 4685^{o}K) from a single 1*1 mm^2 chip:

Philips Lumileds High-Power, White LED		
Current	350 mA	2000 mA
Lumens	136	502
Lumens per Watt	115	61
Watts	1.2	8.3

Several new technologies contributed, some of them will be incorporated in a new generation of products coming out in this quarter …

Summary

- Power LEDs are improving rapidly and continued improvement is expected. Performance of 100 lm/W will happen and ~150 lm/W is likely.
- There are a variety of applications for which single color, RGB, and PC white power LEDs are being utilized and should dominate.
- Key areas for future improvement are IQE (especially green) and phosphors for warm white.
- It is now clear that LEDs also should dominate general illumination. Full conversion at 150 lm/W would "save" over 100 nuclear reactors worldwide.

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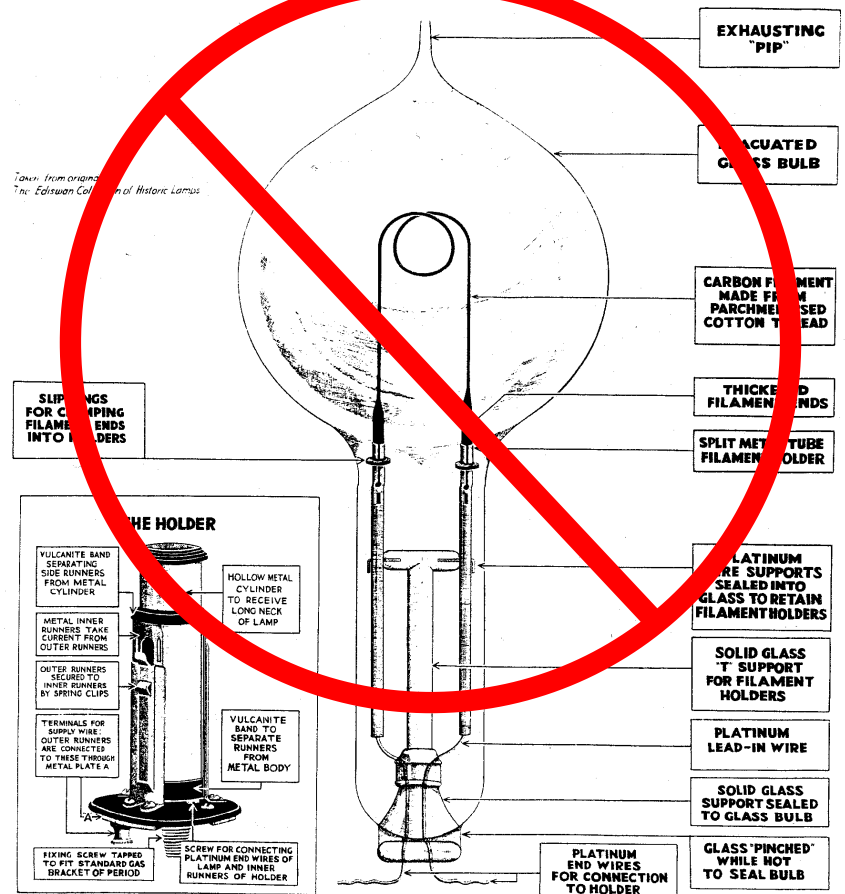
LIGHT FROM SILICON VALLEY

How Long Will It Take??

LENGTHENING THE DAY

LENGTHENING THE DAY



THE FIRST SWAN COMMERCIAL LAMP

MADE BY SWAN'S ELECTRIC LIGHT CO. AT SOUTH BENWELL, NEWCASTLE, ENGLAND, IN

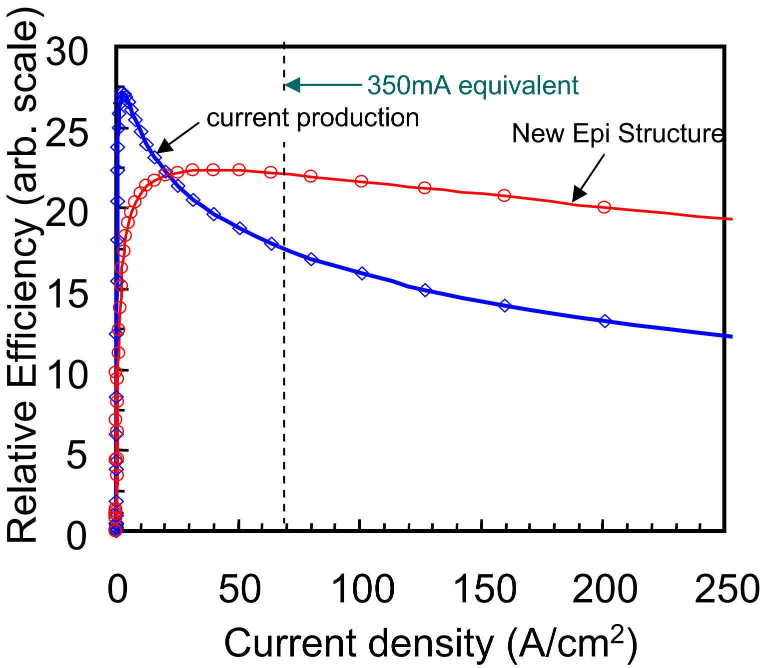
1881

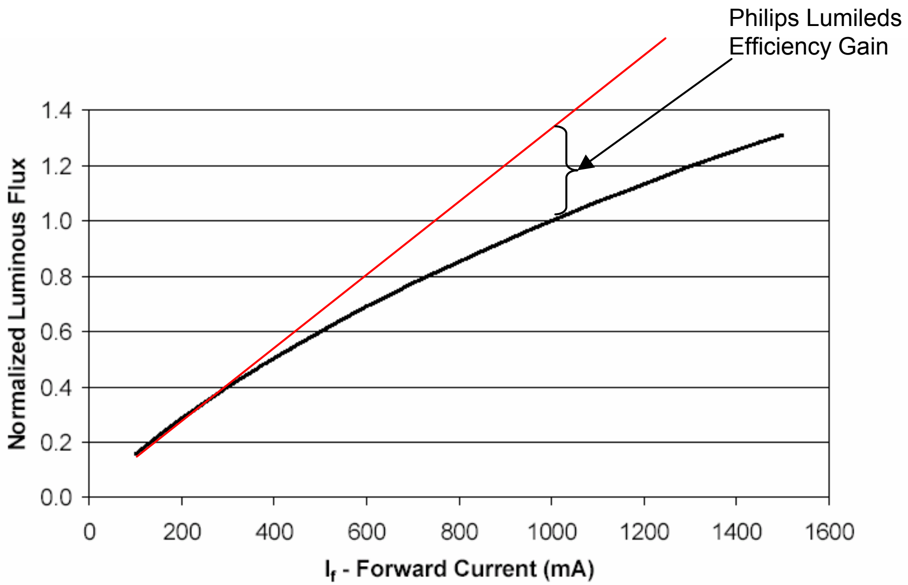
PREPARED BY THE EDISON SWAN ELECTRIC CO. LTD., 155, CHARING CROSS ROAD, LONDON, W.C.2. AND BRANCHES
MAKERS OF THE FAMOUS ROYAL "EDISWAN" LAMPS

Solid-State Lighting Differences

Conventional		SSL Opportunity
Ballast	→	Electronic Driver
Sheet Metal	→	Optics
Guards/screens	→	Heatsink
Dimmer switches	→	Digital Controls Solutions for colour and white

High Efficiency at High Currents





Efficiency droop with current

New epi structure produces substantially more flux at 1A drive.