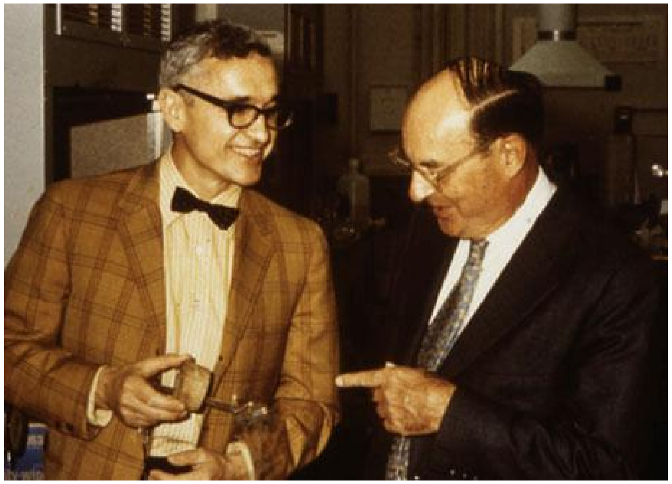
HOW LEDS ARE CHANGING THE WORLD

Mike Krames, PhD

IEEE CNSV Meeting — 7 Oct 2015 — Palo Alto

Semiconductors: Transistors to Light

Bardeen, Shockley, Brattain
AT&T Bell Labs, 1948

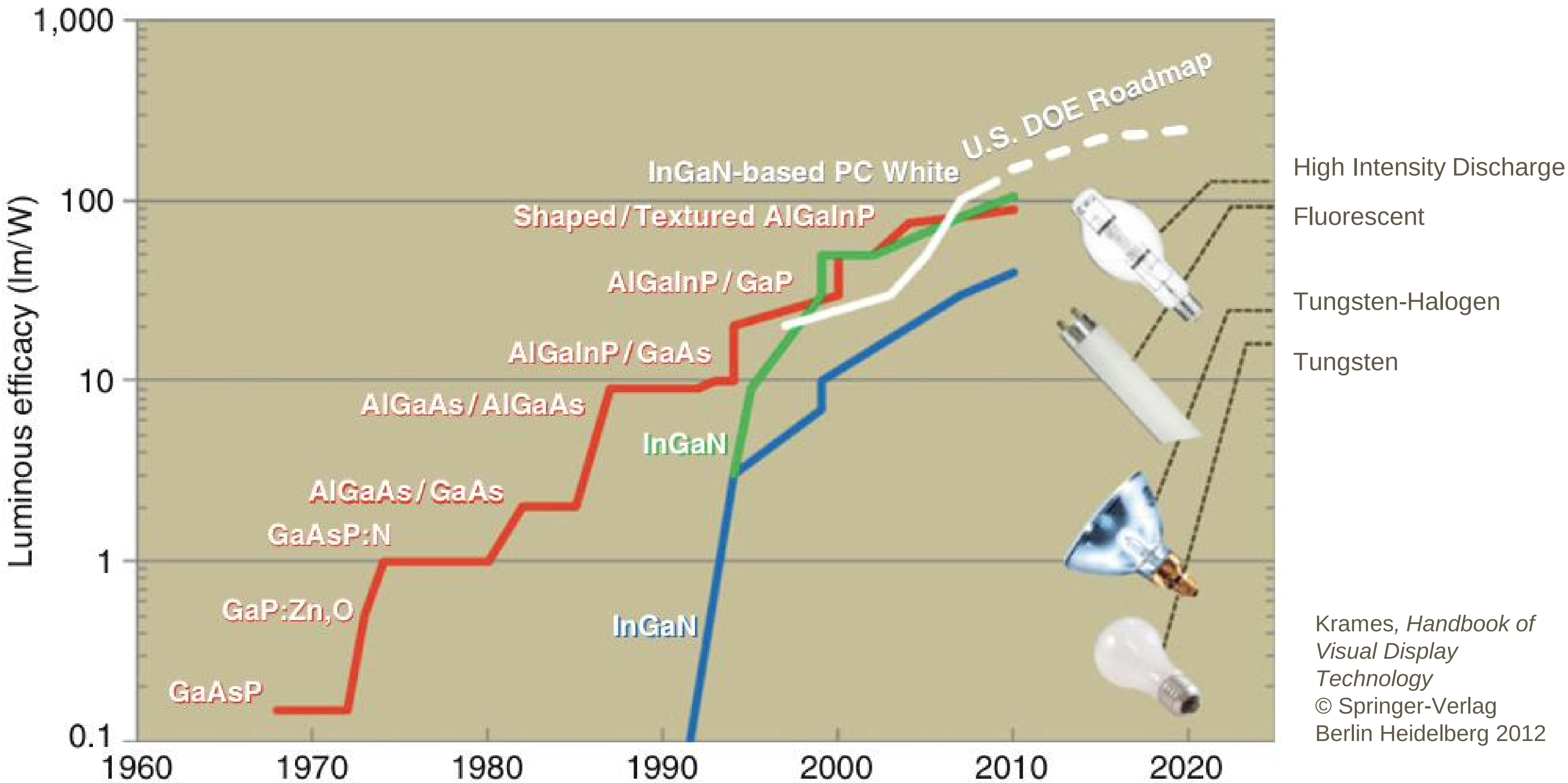


Holonyak & Bardneen
University of Illinois, early 1970s

Krames, Holonyak & Nakamura
University of Illinois, 2012

- [Bardeen '48] Invention of transistor ignited semiconductor materials R&D
- [Holonyak '62] III-V alloy engineering and the first practical visible-spectrum (red) LED
- [Nakamura '91, with Akasaki & Amano] First III-nitride (GaN-based) blue-emitting LED

LED Evolution of Performance



Krames, *Handbook of Visual Display Technology*
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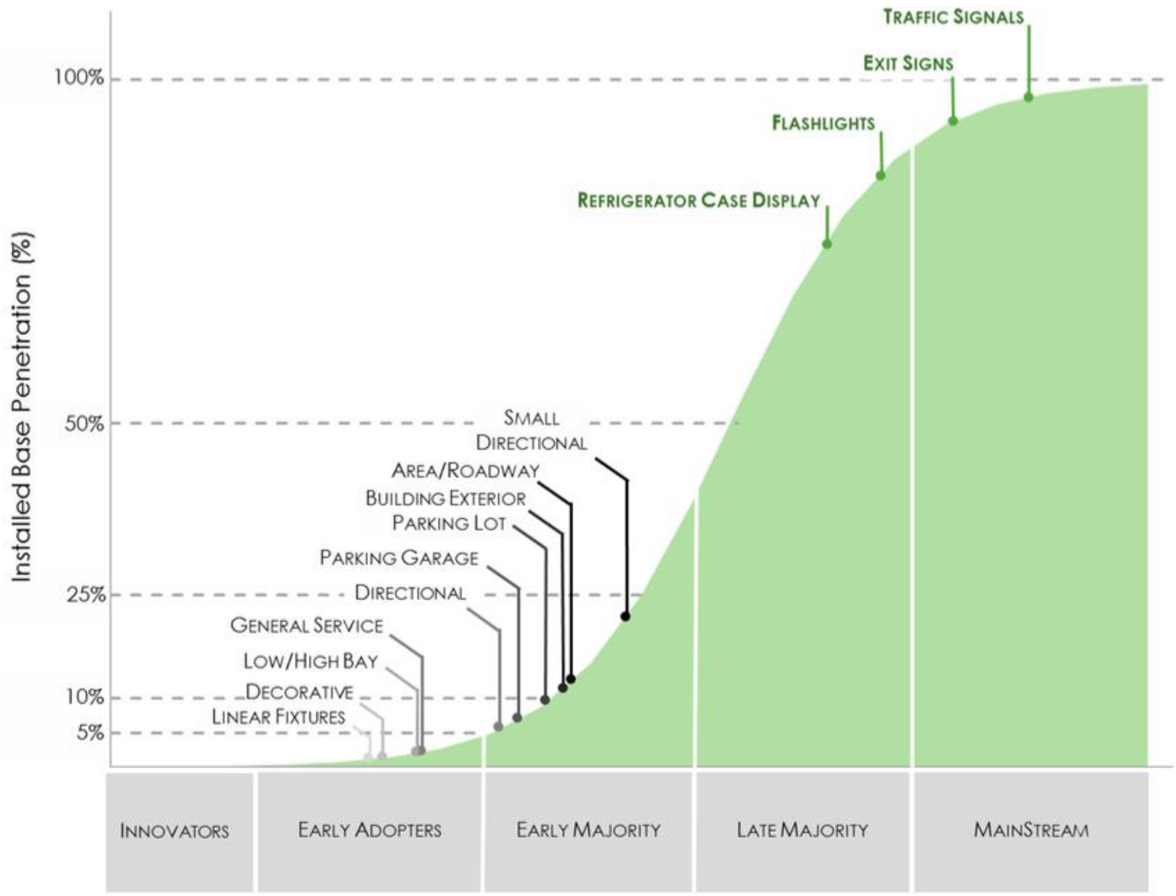
- Exceeds all conventional technologies…

LED Adoption:

Currently < 50%

But accelerating…

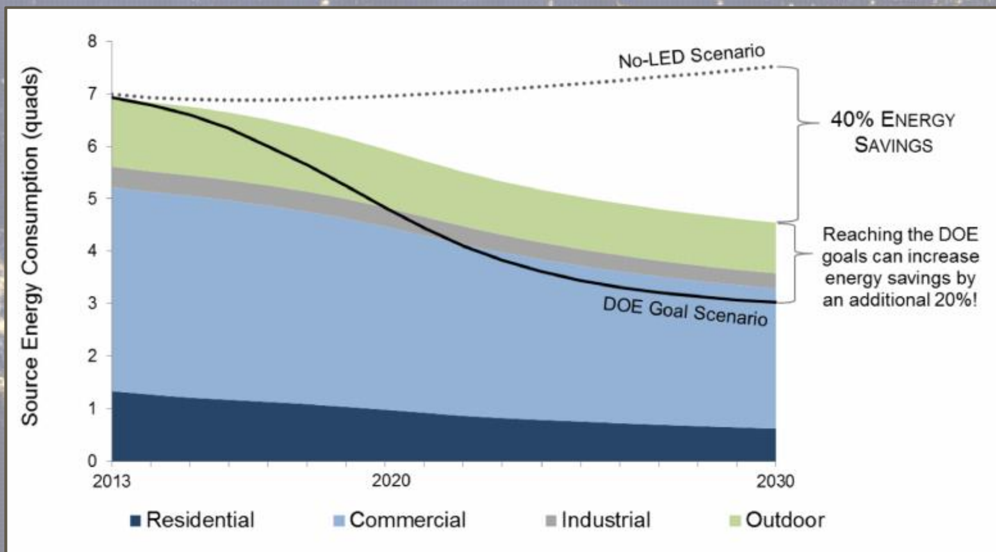


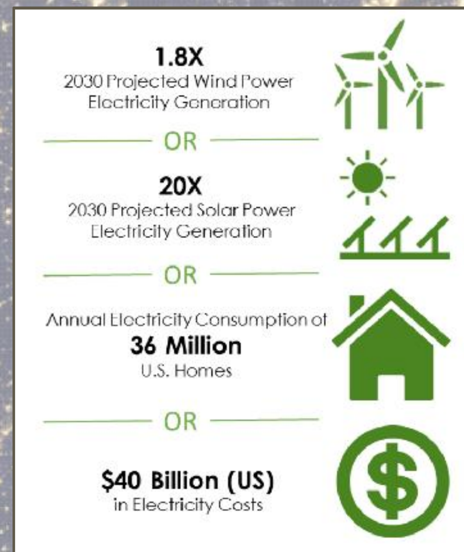
Adoption of Light-Emitting Diodes in Common Lighting Applications
U.S. Department of Energy Solid-State Lighting Program
July 2015

Energy Savings Using LEDs

Total U.S. Lighting Energy Consumption Forecast
2013 to 2030

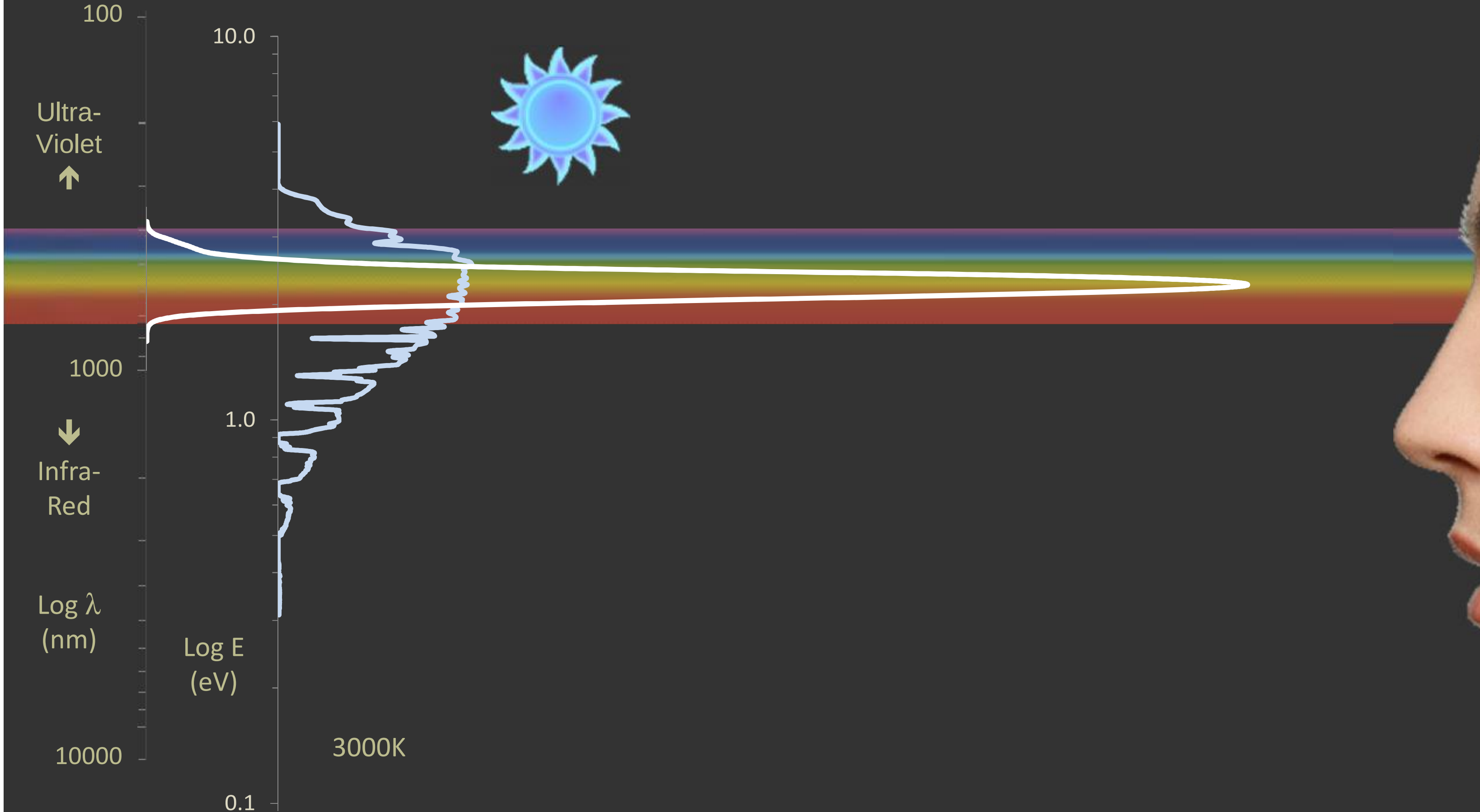
Solid State Lighting R&D Plan
U.S. Department of Energy
May 2015





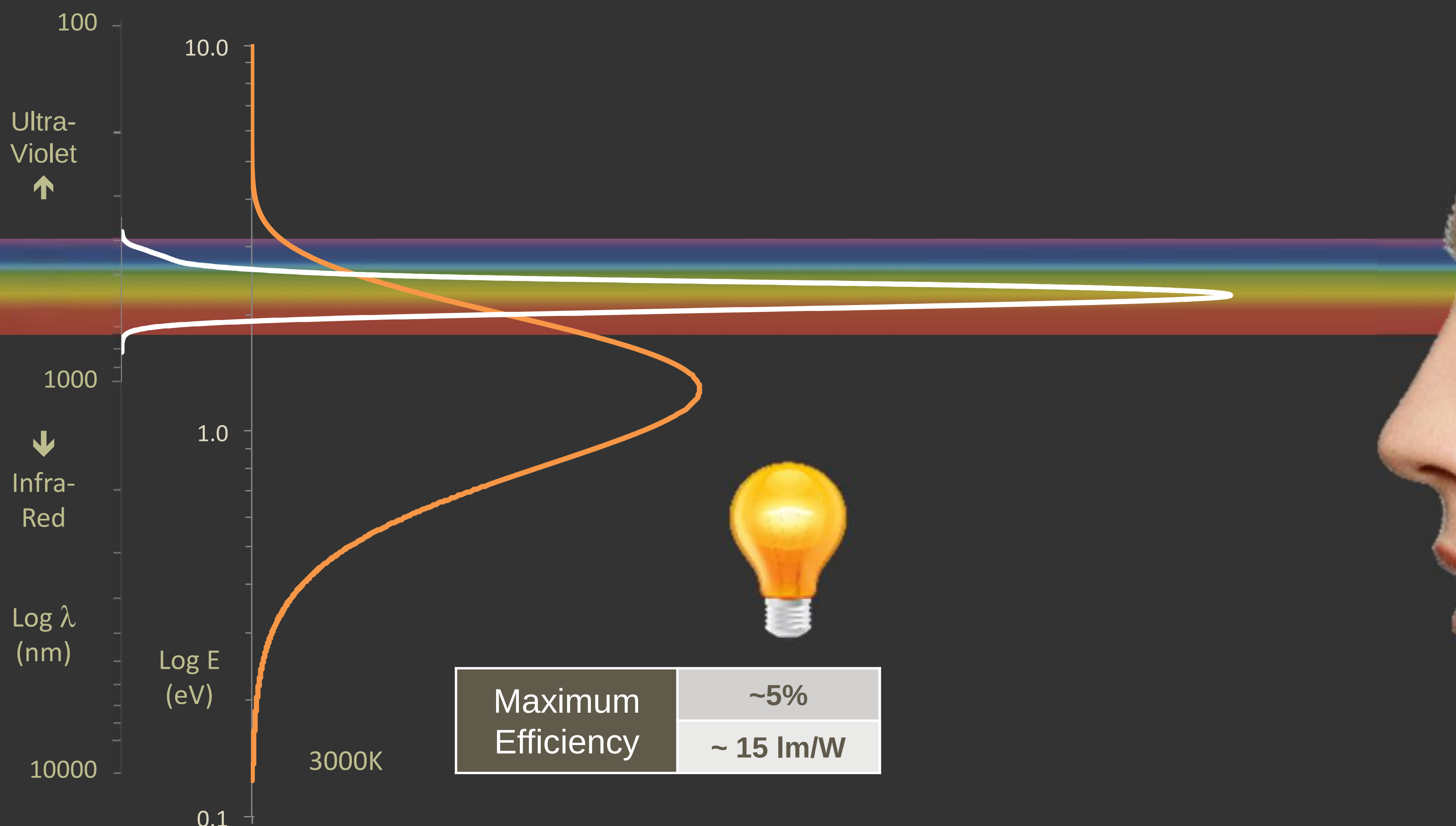
- Target savings of 395,000 gigaWatt-hours per year by 2030
- ~ 50 large coal-fired power stations
- ~ 300 million tons of reduced CO_2 emissions (or 57 M automobiles)

Luminous Efficacy



- One Watt of optical power at 555 nm = 683 lumens
- Typical “white” spectra are 250-350 lumens per Watt (lm/W)

Luminous Efficacy



Maximum Efficiency	~5%
	~ 15 lm/W

- One Watt of optical power at 555 nm = 683 lumens
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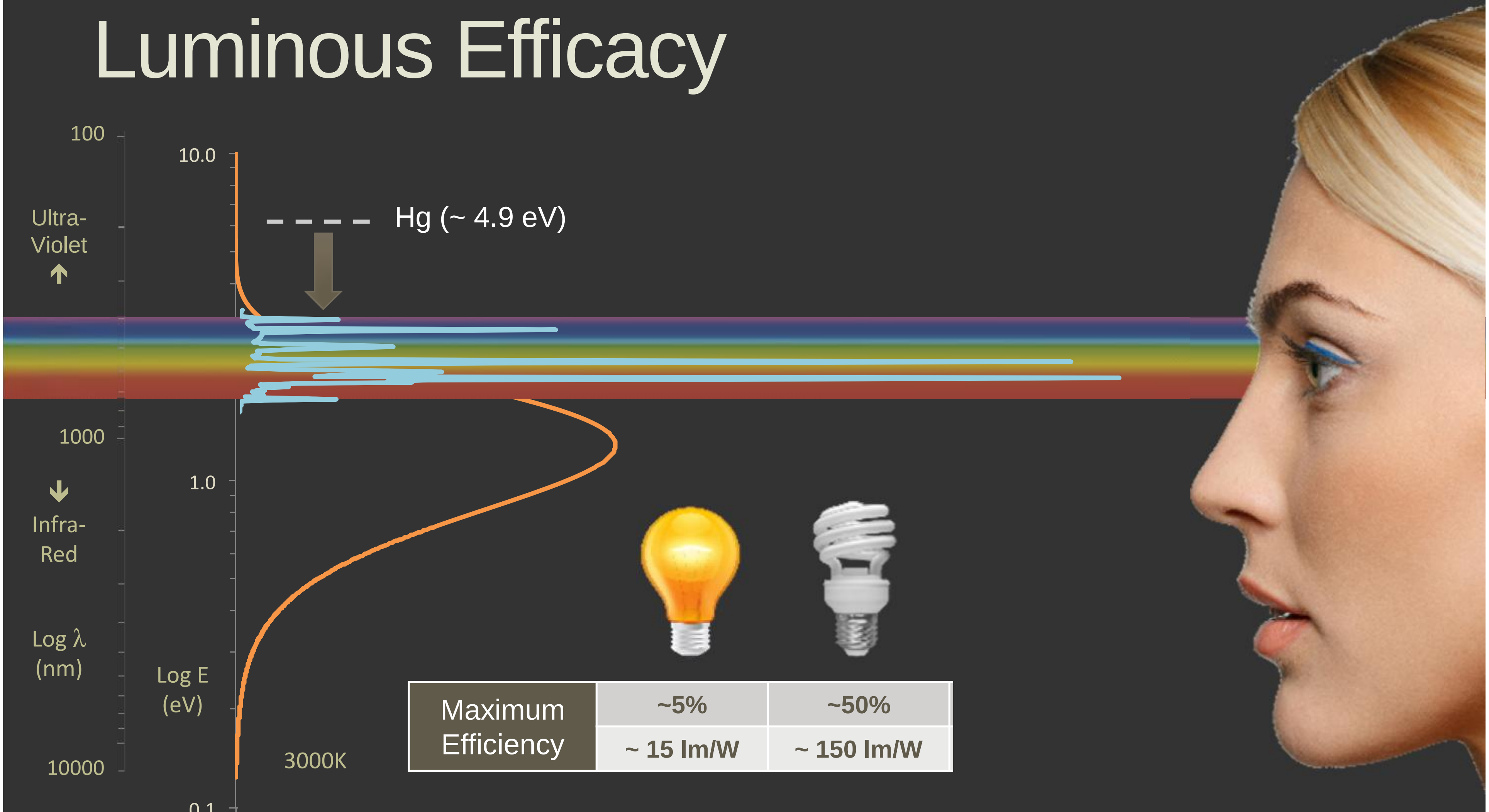
Luminous Efficacy



Maximum Efficiency	~5%	~50%
	~ 15 lm/W	~ 150 lm/W

- One Watt of optical power at 555 nm = 683 lumens
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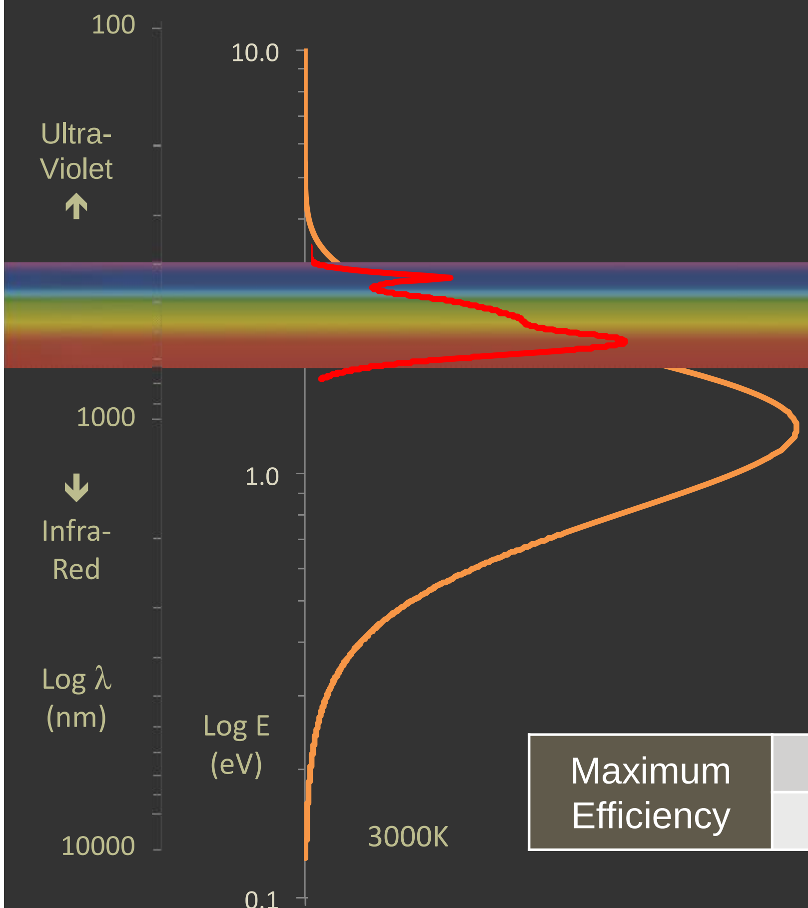
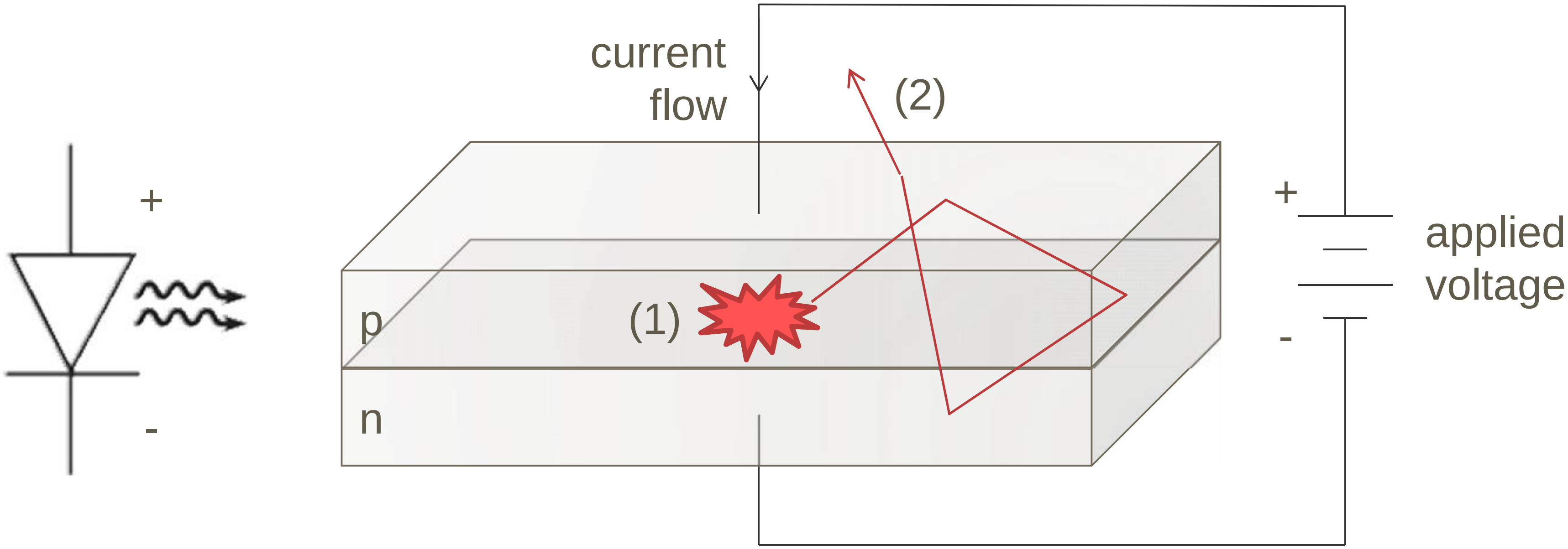
Luminous Efficacy



Maximum Efficiency	~5%	~50%	~80-100%
	~ 15 lm/W	~ 150 lm/W	~ 250-300 lm/W

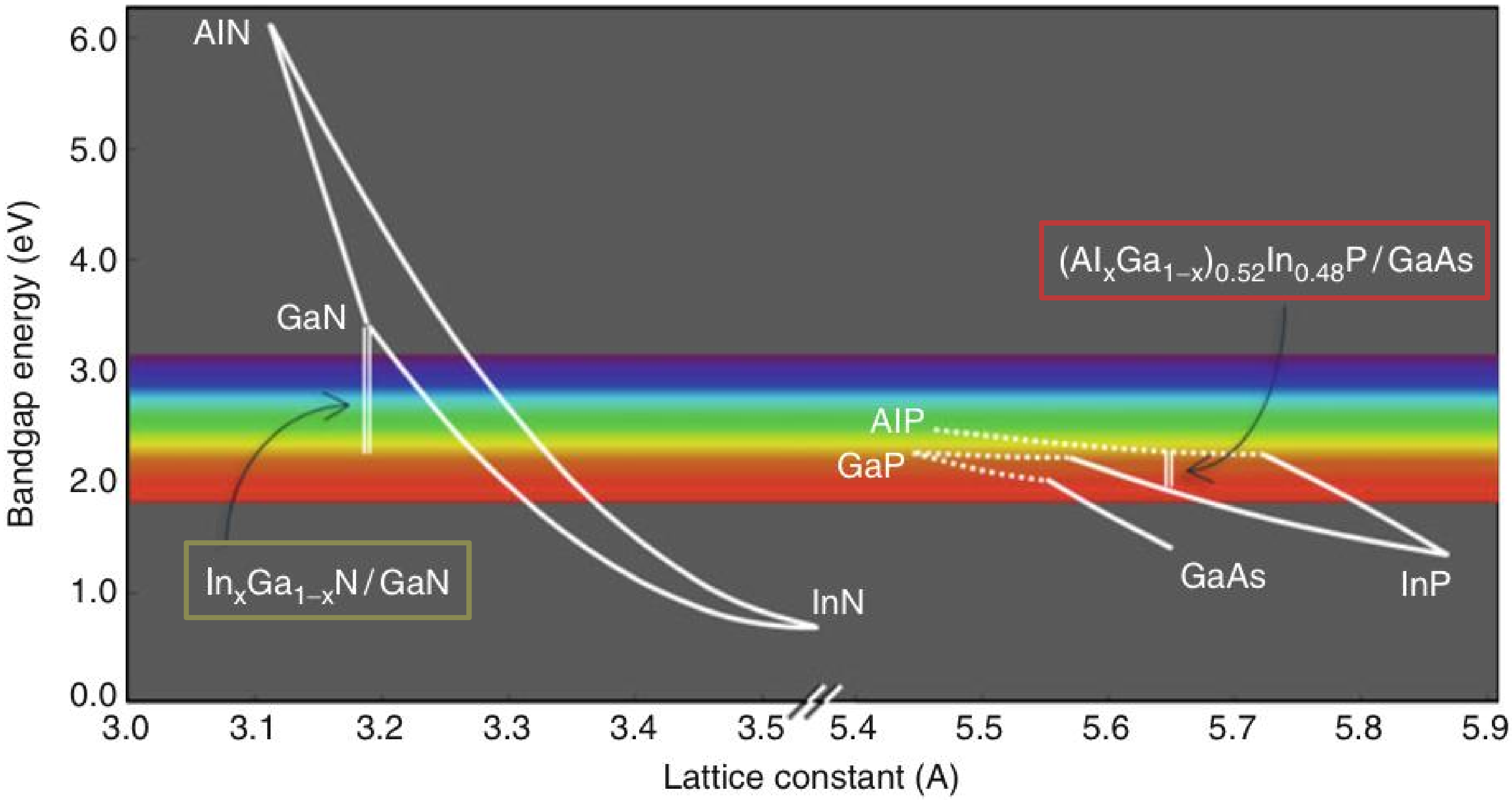
- One Watt of optical power at 555 nm = 683 lumens
- Typical "white" spectra are 250-350 lumens per Watt (lm/W)

LED Fundamentals



- External Quantum Efficiency (EQE): % injected electrons generating photons emitting outside LED chip
  - EQE is a product of:
    - (1) Internal Quantum Efficiency: % injected electrons generating photons *inside LED chip*
    - (2) Chip light extraction efficiency: fraction of photons that *escape LED chip*

LED Material Systems



Krames, *Handbook of Visual Display Technology*
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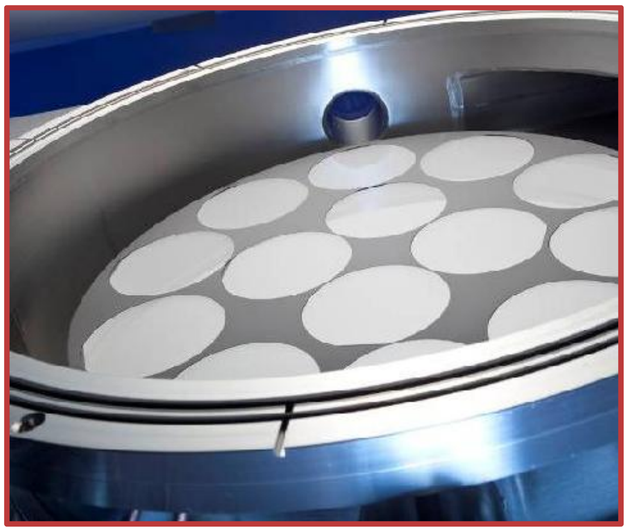
- (Al,Ga)InP: red to amber
- (In,Ga)N: green to blue to UV-A

Manufacturing: Epitaxy

- Device layers deposited via Metal Organic Chemical Vapor Deposition (MOCVD)
- Layer control to the nanometer level (e.g., quantum wells)
- Control over temperature to less than 1°C at 800°C (InGaN)

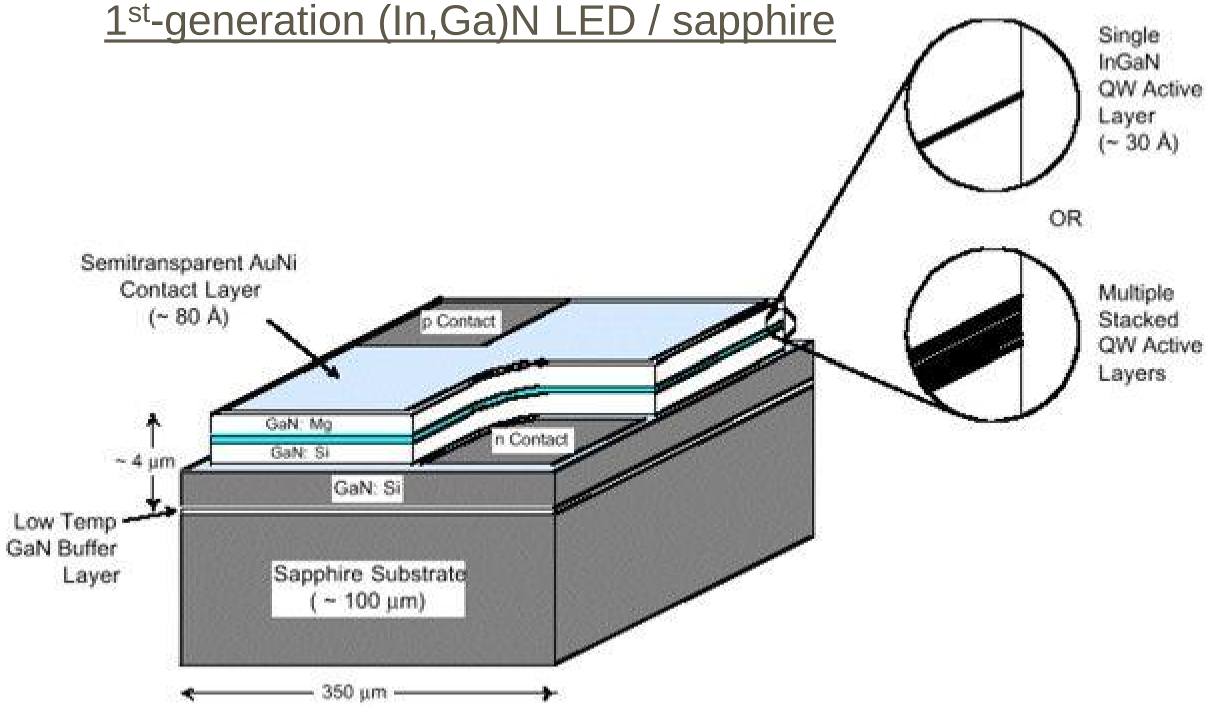


Substrate choice	(Al,Ga)InP	(In,Ga)N
	GaAs, Ge	Al_2O_3, SiC, Si, GaN

Manufacturing: Chip Fabrication

- Mg "activation"
- Semi-transparent p Ohmic contact
- p electrode
- Mesa etch
- n Ohmic contact
- Singulation

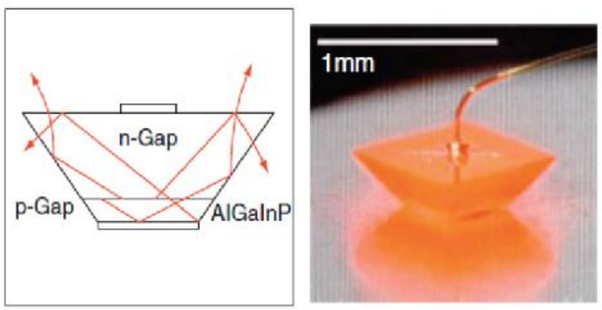
1st-generation (In,Ga)N LED / sapphire



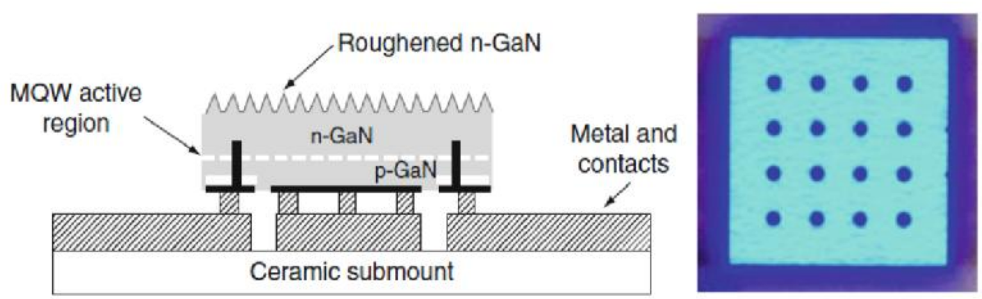
Light Extraction Efficiency

- Dense materials with refractive index, n ~ 2.4 (GaN) to 3.3 (GaP)
- Probability to escape surface ~ $1/n^2$ ➔ only 5-10% per pass

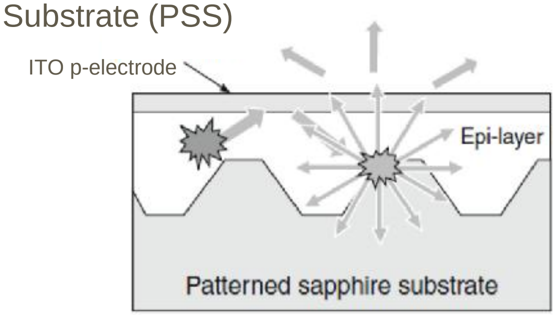
Shaped Transparent Substrate (TS) - GaP



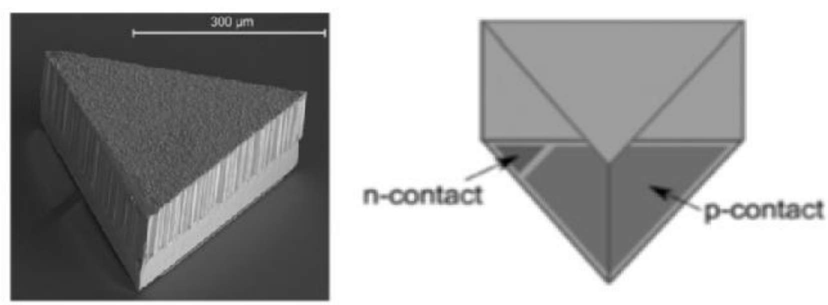
Thin-Film Flip-Chip (TF-FC)



Indium-Tin-Oxide (ITO) & Patterned Sapphire Substrate (PSS)



Shaped Transparent Substrate (TS) - GaN



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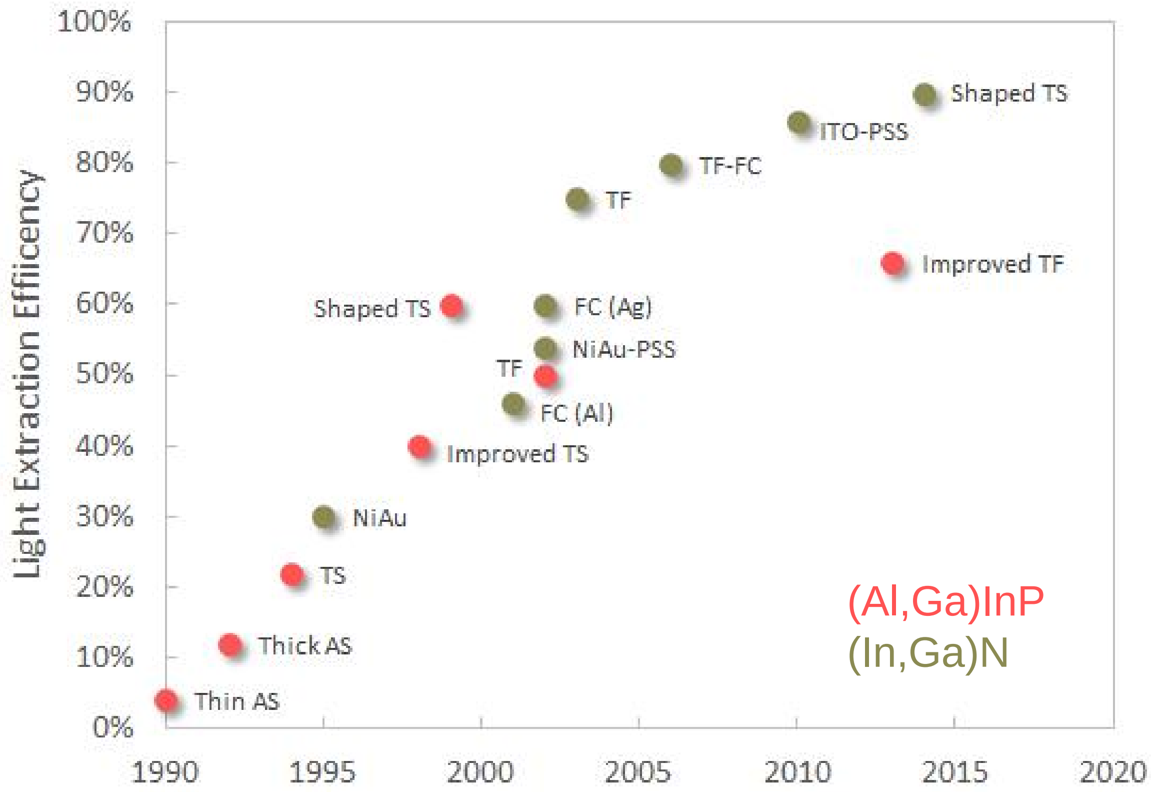
Hurni *et al.*, Applied Physics Letters 106, 031101 (2015)

Light Extraction Efficiency



AS	absorbing substrate
TS	transparent substrate
NiAu	nickel-gold
Al	aluminum
Ag	silver
FC	flip-chip
TF	thin-film
ITO	indium-tin-oxide
PSS	patterned sapphire substrate

- For GaN, nearing theoretical limits (90%)
- For (Al,Ga)InP, high refractive index and internal losses remain a challenge

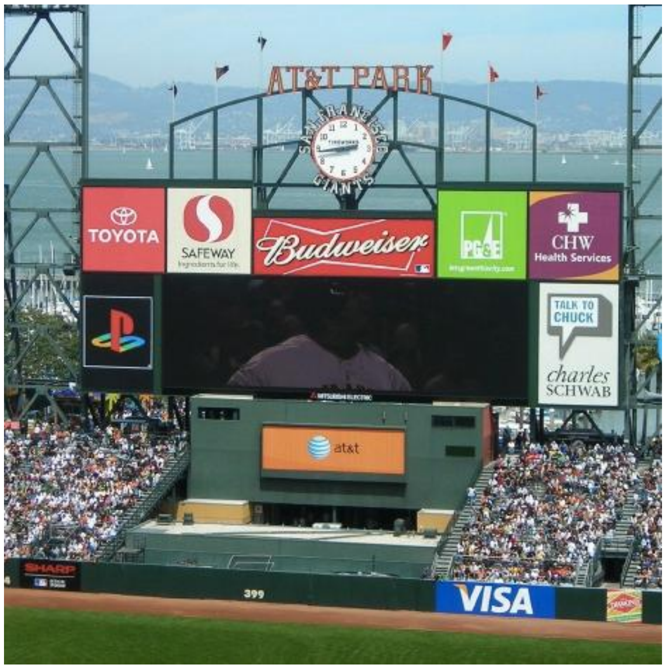
Manufacturing: Packaging I

- Low Power
  - 5 to 50 mA
  - “T1 ¾” circa 1970s+

- Mid Power
  - 50 to 150 mA
  - “SnapLED” circa 1990+

- High Power
  - 150 mA to 3 A
  - Luxeon™ circa 2000+

Application: Signaling & Signage



White Emitting LEDs

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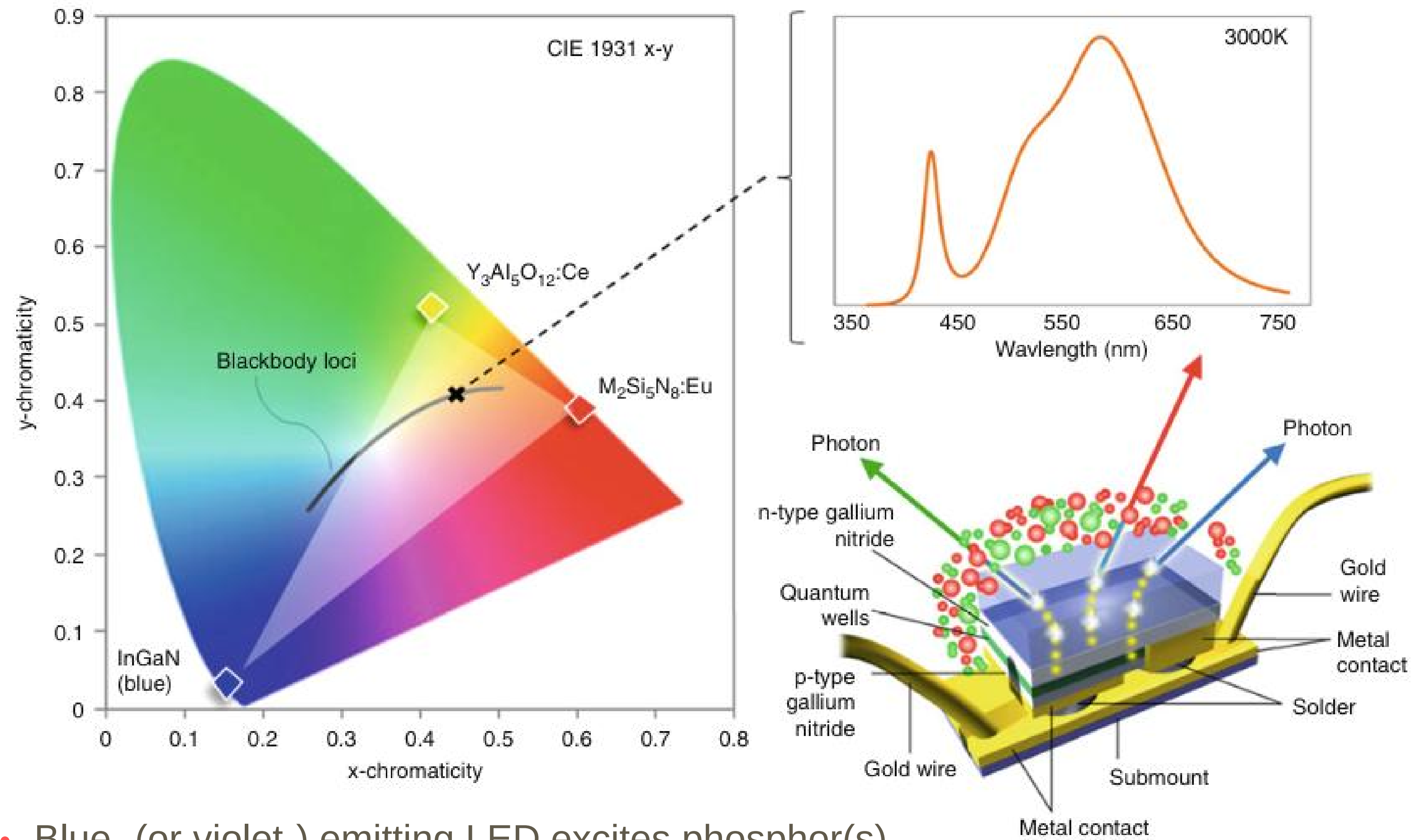


- Blue- (or violet-) emitting LED excites phosphor(s)
- Almost any color realizable
- “Whites ranging” from low color temperature (~1800K) to high (~5000K)

LED Down-Conversion Materials

Phosphors

- (Y,Al)O:Ce – yellow; from scintillators
- (Lu,Al)O:Ce – green; another “garnet”
- 2-5-8 Nitrides – red, amber; “new” last decade
- GE’s “PFS” – line-emitter for LEDs

Quantum Dots

- Semiconductor nanoparticles, aka “quantum dots”
- Cd(S,Se)
- (In,Ga)P
- Now deployed in flat-panel displays

Manufacturing: Packaging II

Today

- Low Power
  - 5 to 50 mA
  - “T1 ¾” circa 1970s+

4 mm x 1 mm

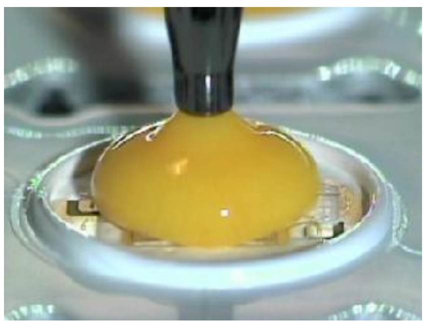
- Mid Power
  - 50 to 150 mA
  - “SnapLED” circa 1990+

3 mm x 3 mm

- High Power
  - 150 mA to 3 A
  - Luxeon™ circa 2000+

3 mm x 5 mm

Manufacturing: Packaging II



Lumileds

- Phosphor incorporation a major driver for package design and manufacturing processes
  - e.g., "Chip-On-Board" LEDs for high-output directional lighting
- Packaging sophistication as efficiency has improved (less heat generation)
  - e.g., LED "chip-scale package" (CSP) to reduce and eliminate package elements

Application: Displays & Imaging

Application: Retrofit Lamps

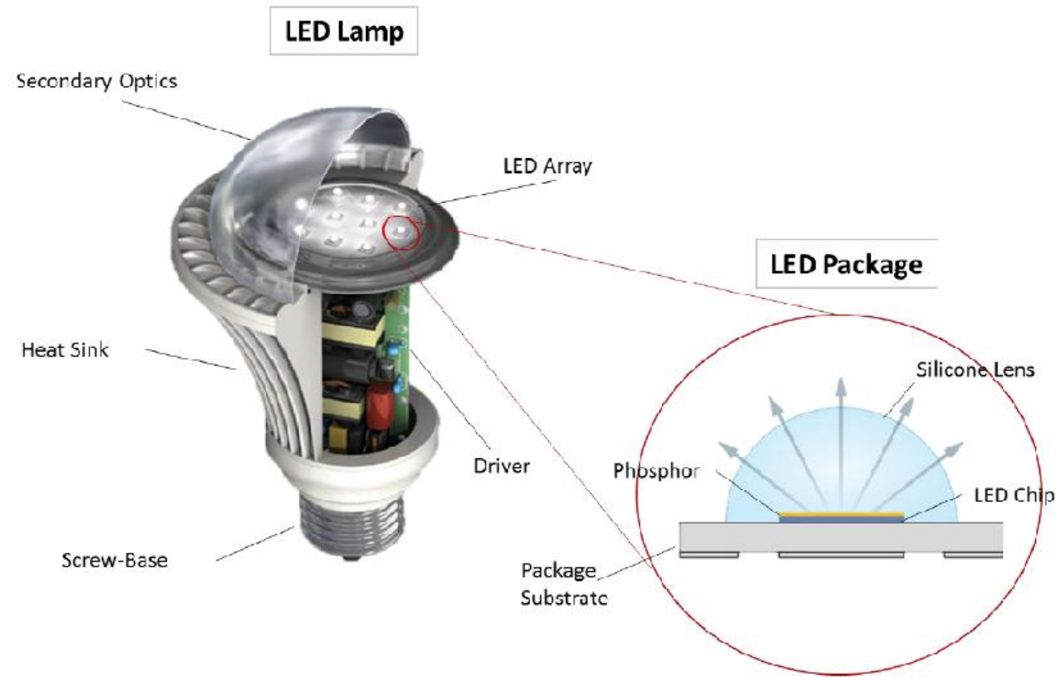


Image Sources: a) Lamp: http://electronics.stackexchange.com/questions/76883/how-do-led-light-bulbs-work, b) Package: Tuttle & McClear, LED Magazine Feb. 2014.

www.soraa.com

- “60-Watt equivalent” for less than 10 W
- Surpassing halogen directional performance (Soraa, 2012): 50 ➔ 7 Watts
- A platform for energy saving controls, and big data

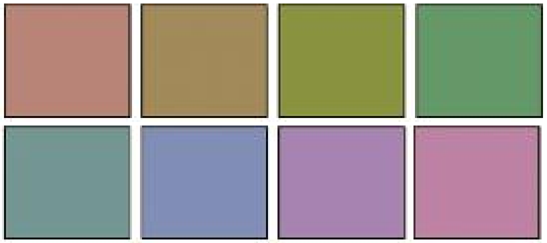
Application: Luminaires

Outdoor

Indoor

- Much better light utilization & dramatic energy savings
- New design capability
- Further improvements utilizing controls (e.g., proximity sensors, etc.)

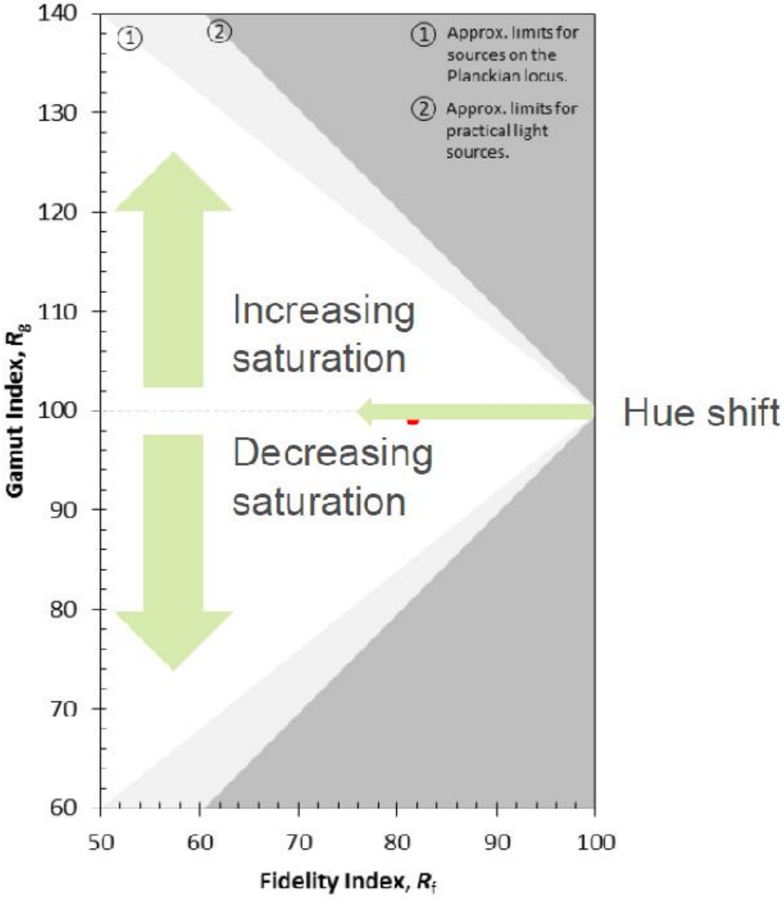
Light Quality: Color



Eight "pastel" Munsell samples used for CRI

www.soraa.com

Royer, LightFair 2015

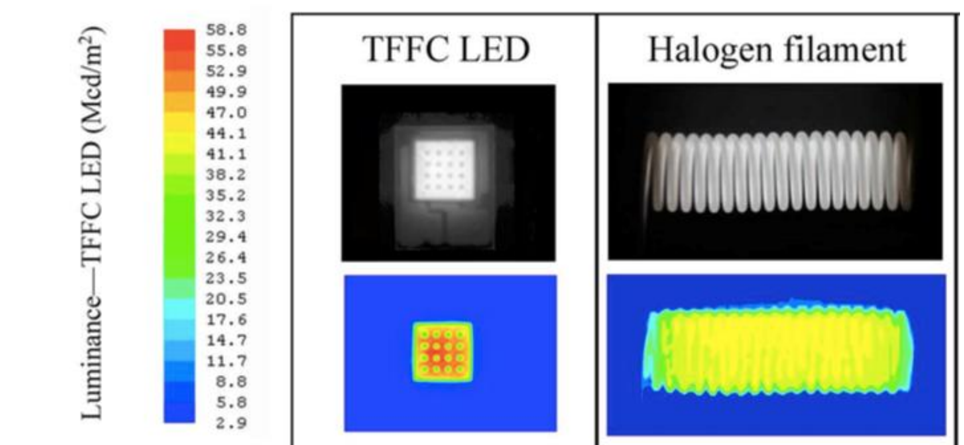


- Color Rendering Index (CRI, or R_a) – limited
- CRI 80 is minimum for ENERGY STAR
- IES TM-30 color fidelity metric (R_f) – 99 colors
- Optical brightening agent "whiteness rendering" – ?

Light Quality: Health

- Human circadian clock regulated by blue light (non-visual photo-receptor) – Brainard et al.
- Most LEDs are based on blue primary emitters
- Attention should be placed on time / location of light sources and/or their emission spectrum

Application: Automotive



	TFFC LED	Halogen filament
Avg. Luminance	50	20-30
Flux out (Power in)	158 (< 4) ea.	1500 (55)
Flux on road (%)	90-130 ea. (~60-80%)	400-600 (~25-40%)

Krames et al., IEEE J Disp Technol 3, 160, 2007

Audi R8

- Brightness exceeding halogen filament, 2007
- First LED headlights, circa 2008
- Moving towards mass adoption

Lumileds' Altilon

Application: Internet of Things

The Future: Illumination

CoeLux S.r.l. in Italy capture both sun and sky in an LED luminaire.

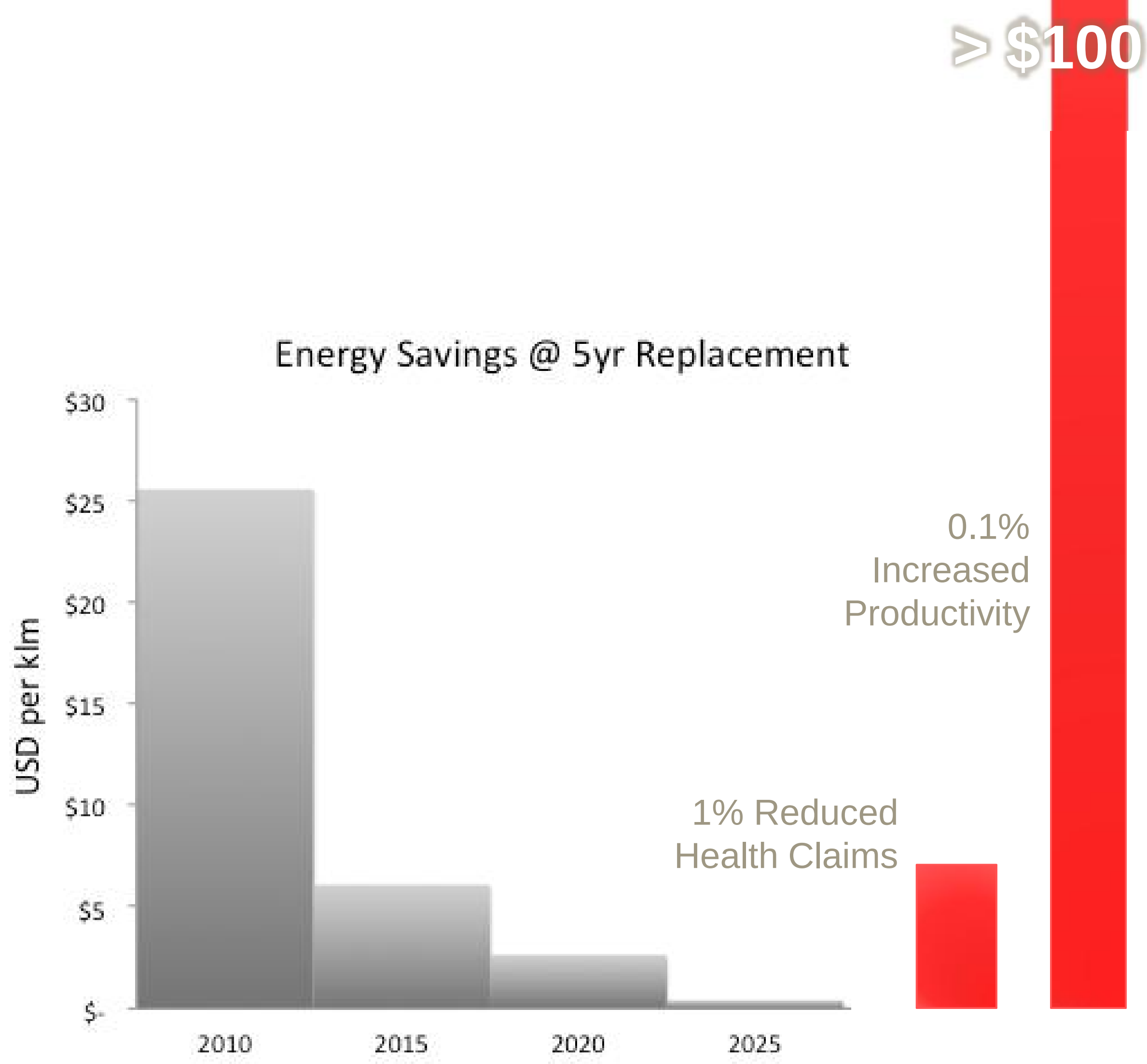
The Future: Illumination

CoeLux S.r.l. in Italy capture both sun and sky in an LED luminaire.

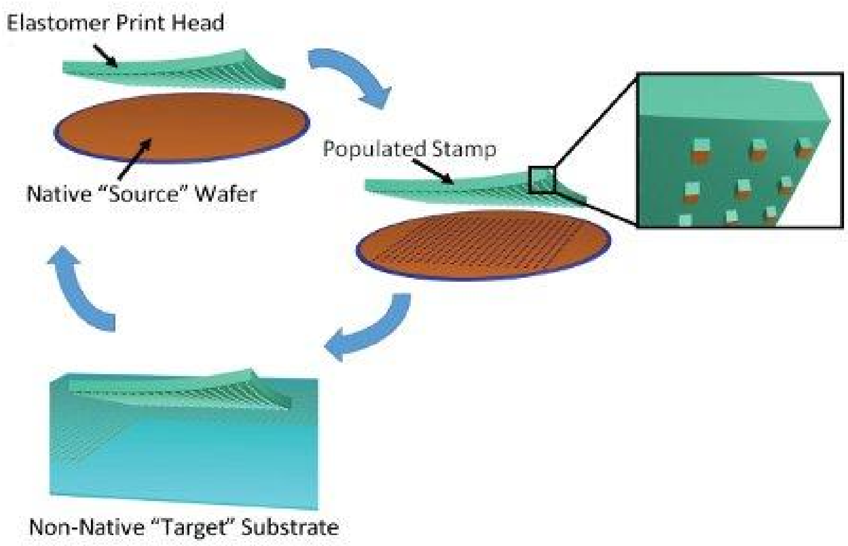
Future: Health & Productivity

"Human Centric Lighting" will drive value creation

Lighting designs must be "healthy"



Future: Displays



1.4" passive matrix display
3 um x 10 um LEDs

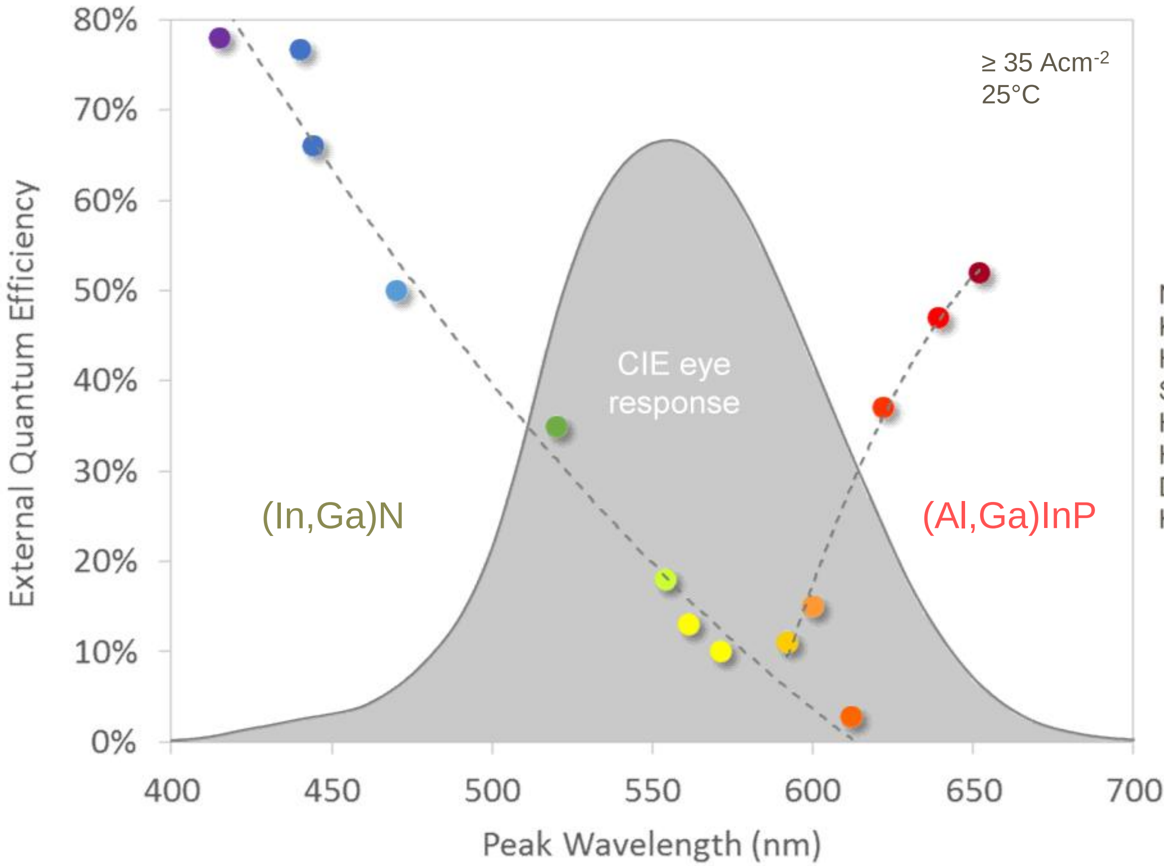
Images courtesy of X-Celeprint, Ltd.

- LCD panel transmissivity typically less than 5%
- Opportunity for direct-emitting *inorganic* LED displays
  - > 10x power reduction
  - Higher color gamut
  - Daylight viewability (!)

Future: Internet of Light

- LED light modulation “LiFi” communication with personal device
- Commissioned LED lights ➔ “indoor GPS” with sub-meter location accuracy

Status LED Performance

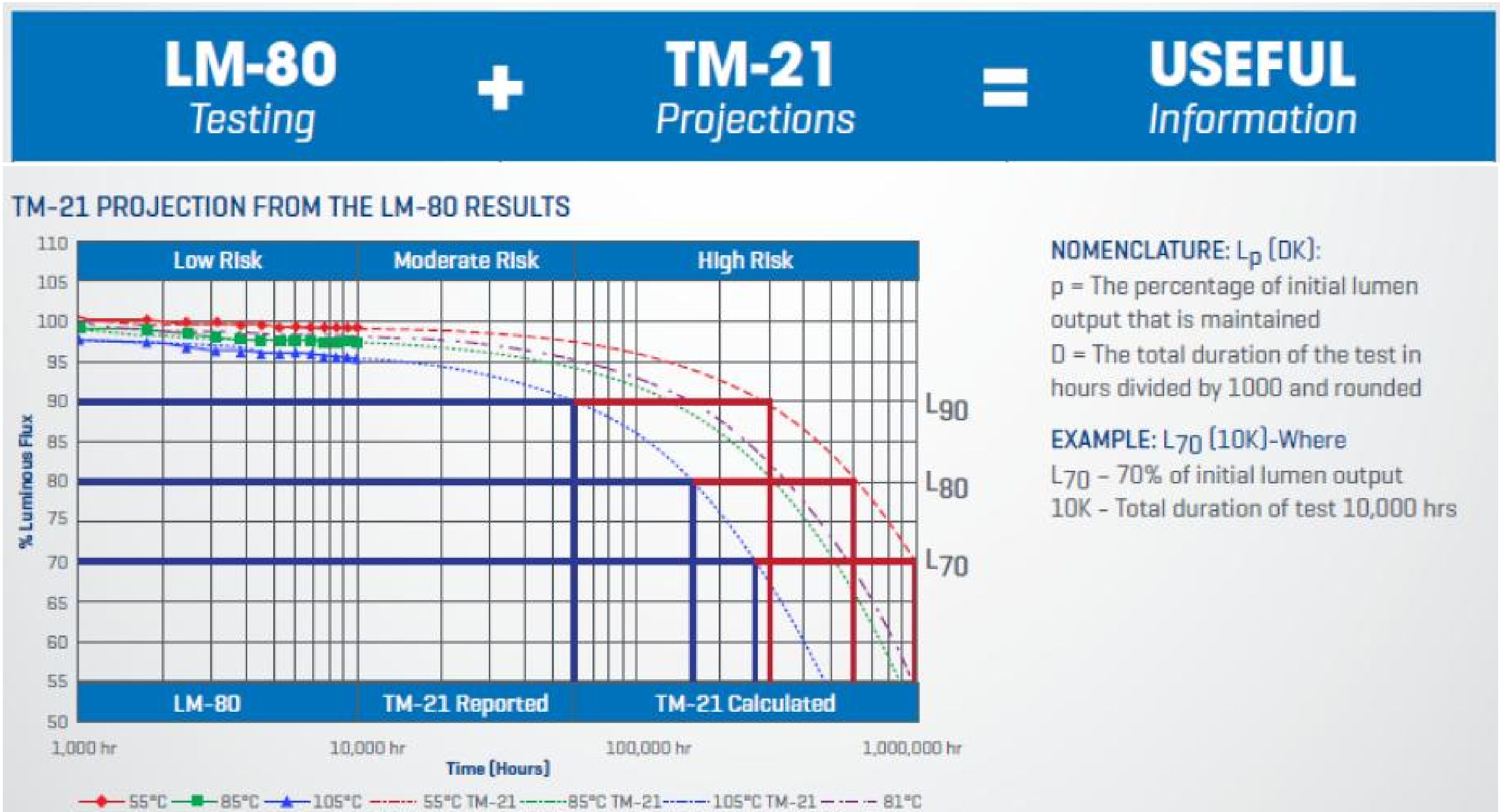


Narukawa et al., J. Phys. D 43, 354002 (2010)
Krames, Handbook Vis. Disp.Tech. (2012)
Hashimoto et al., Phys. Stat. Sol. C 10, 1529 (2013)
Saito et al., APEX 6, 111004 (2013)
Hashimoto et al., Phys. Stat. Sol. C 11: 628 (2014)
Hwang et al., APEX 7, 071003 (2014)
Deb, Lumileds (2015)
Hurni et al., APL 106, 031101 (2015)

- (Al,Ga)InP: bandstructure limitations, esp. at higher temperatures
- (In,Ga)N: strain and miscibility issues with increasing [InN] fraction

LED Reliability

Courtesy D. Hamilton, Hubbell Lighting



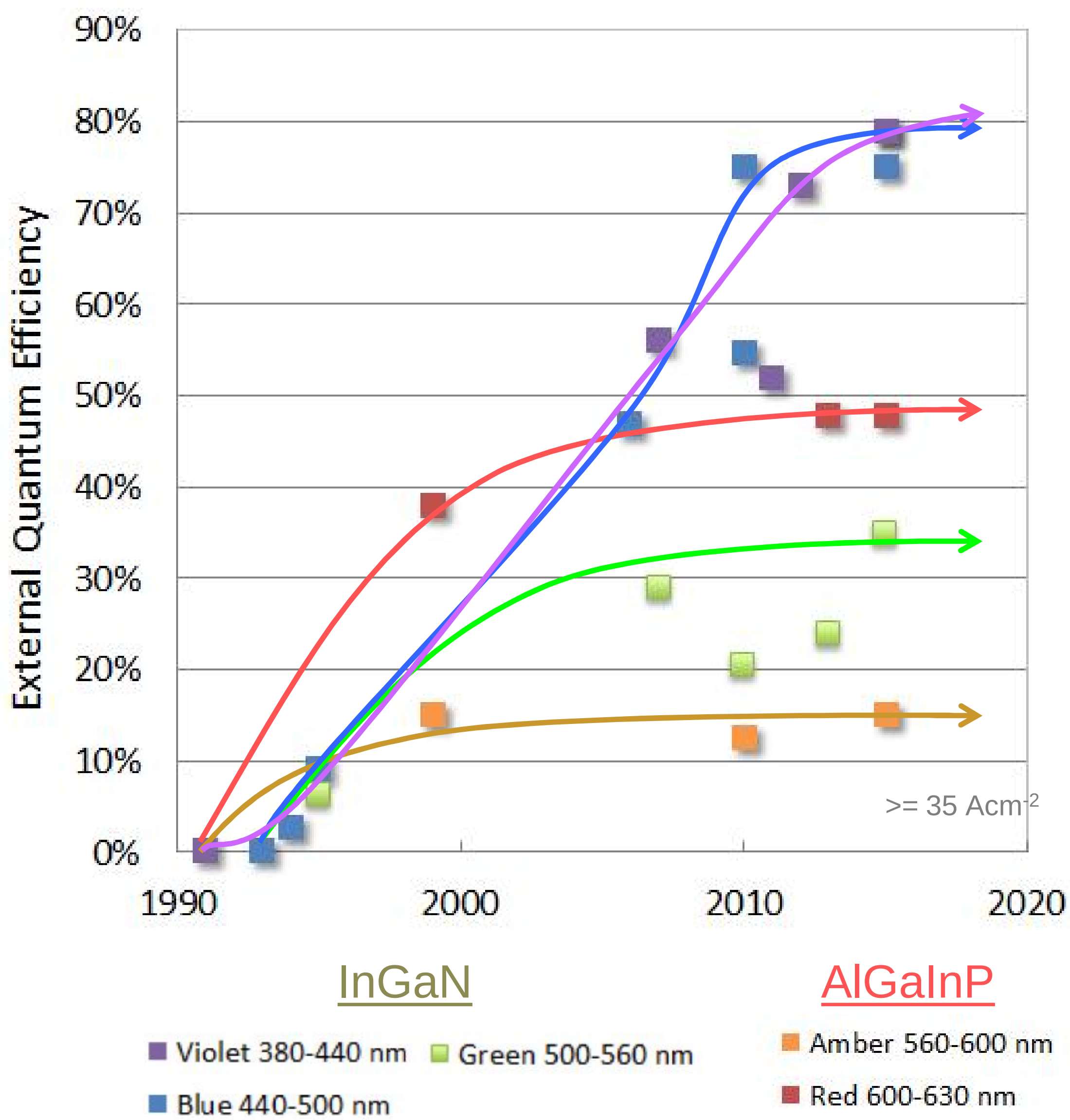
- Illuminating Engineering Society (IES) guides standards (e.g., ENERGY STAR)
- What is missing: Something similar for electronic drivers…!

The Future: LED Performance

Blue & Violet exhibit classic “s-curve” behavior ➔ nearing theoretical limits

Green, Amber, & Red emitters do not ➔ efficiencies have stalled

Opportunities for new research & development



THANK YOU