PHILIPS

sense and simplicity

Solid State Lighting

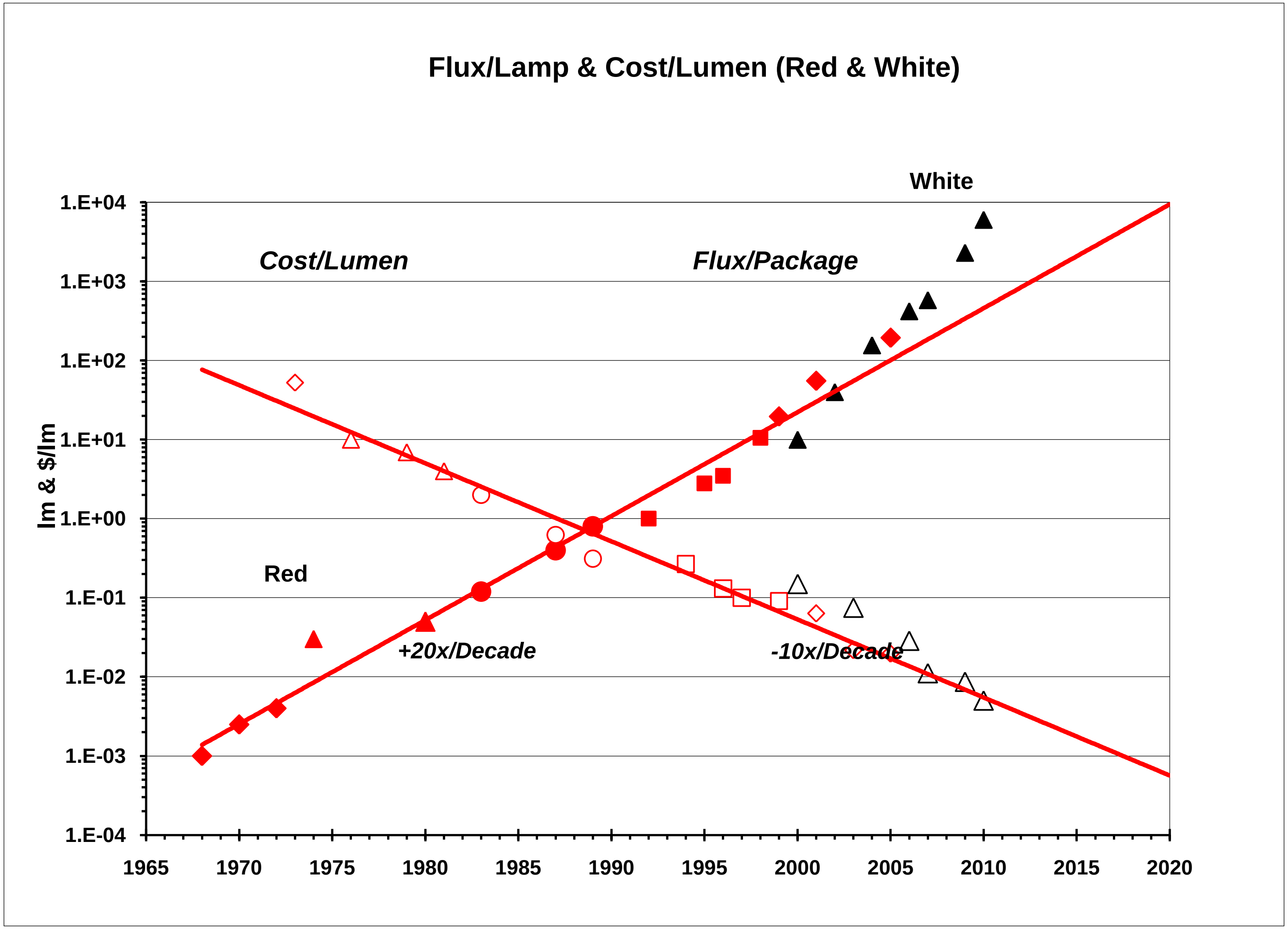
October 2010

LUMILEDS
LIGHT FROM SILICON VALLEY

Agenda

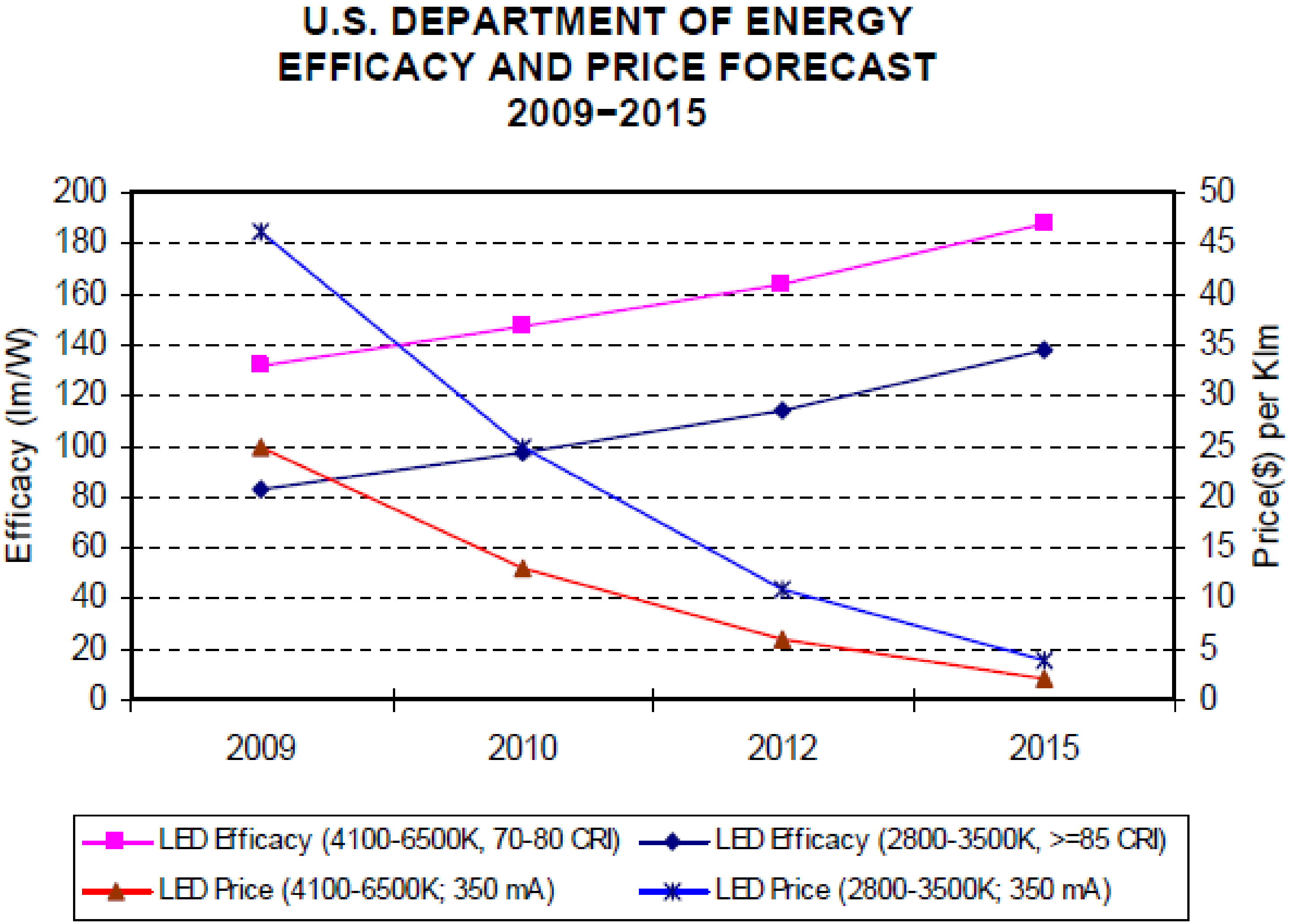
1. SSL Market Forecast
2. Industry Targets
3. LED Technology
4. Major Challenges and Potential Ways Forward

Haitz Efficacy and Price Roadmap: March 2010



Source & Courtesy Of: Roland Haitz

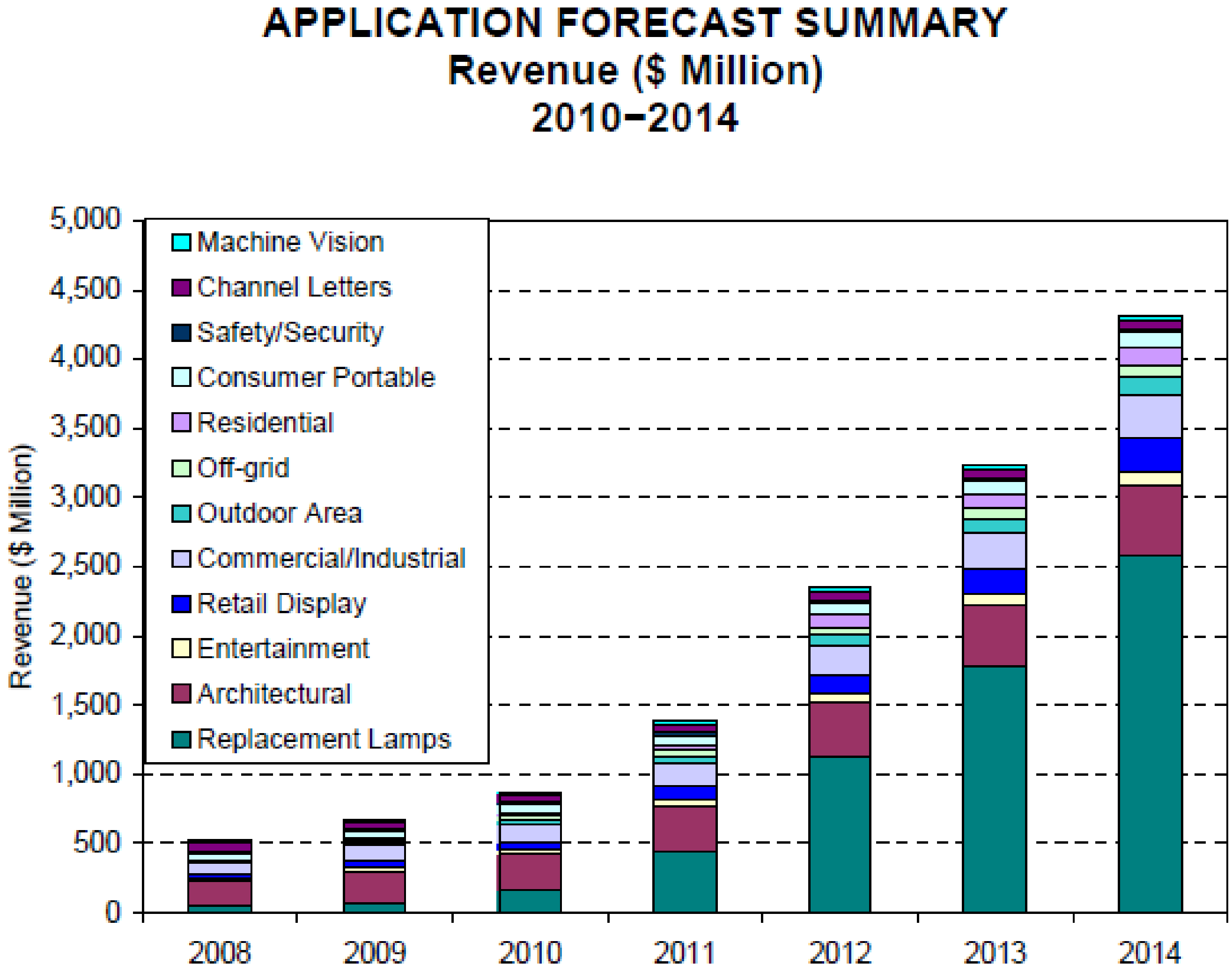
DOE Efficacy and Price Roadmap



U.S. DEPARTMENT OF ENERGY
EFFICACY AND PRICE FORECAST
2009–2015

Source & Courtesy Of: Strategies Unlimited

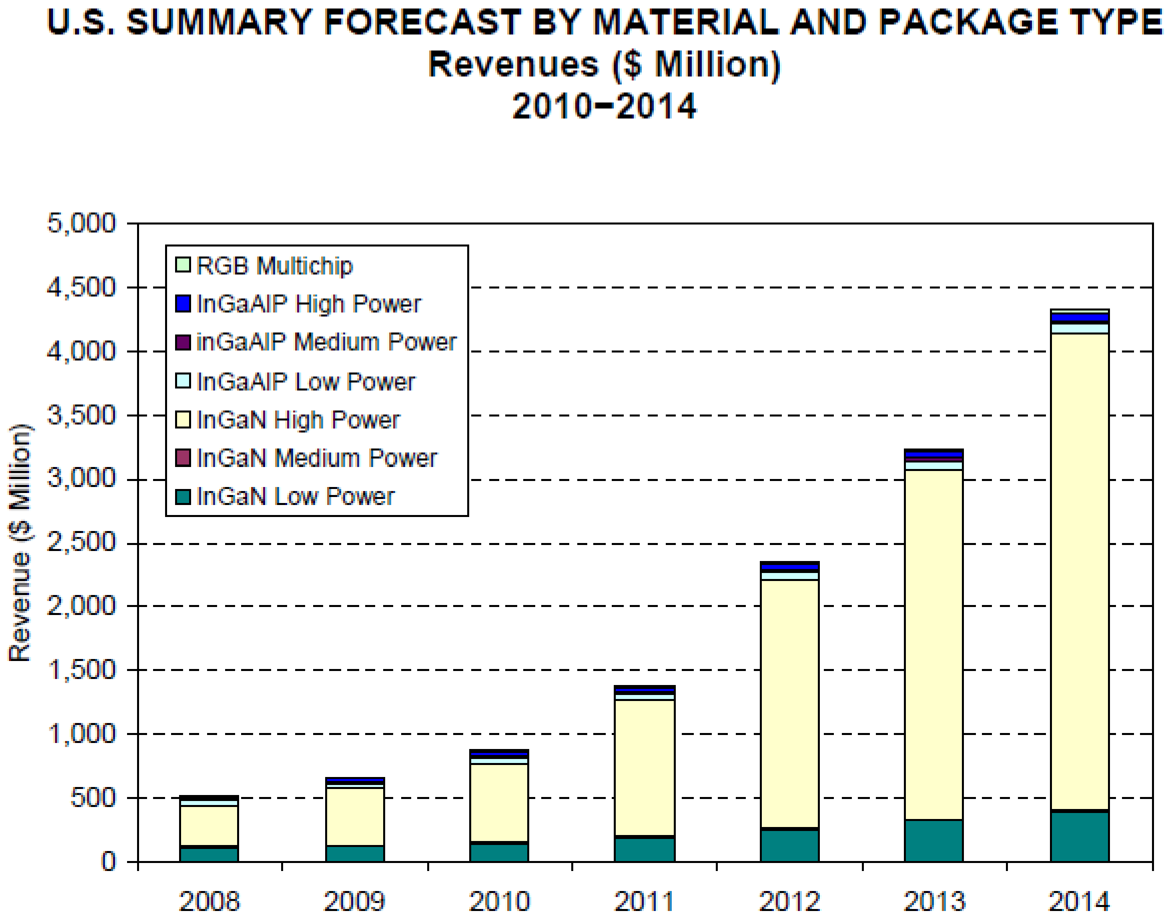
Major SSL Market Sectors



APPLICATION FORECAST SUMMARY
Revenue ($ Million)
2010–2014

Source & Courtesy Of: Strategies Unlimited

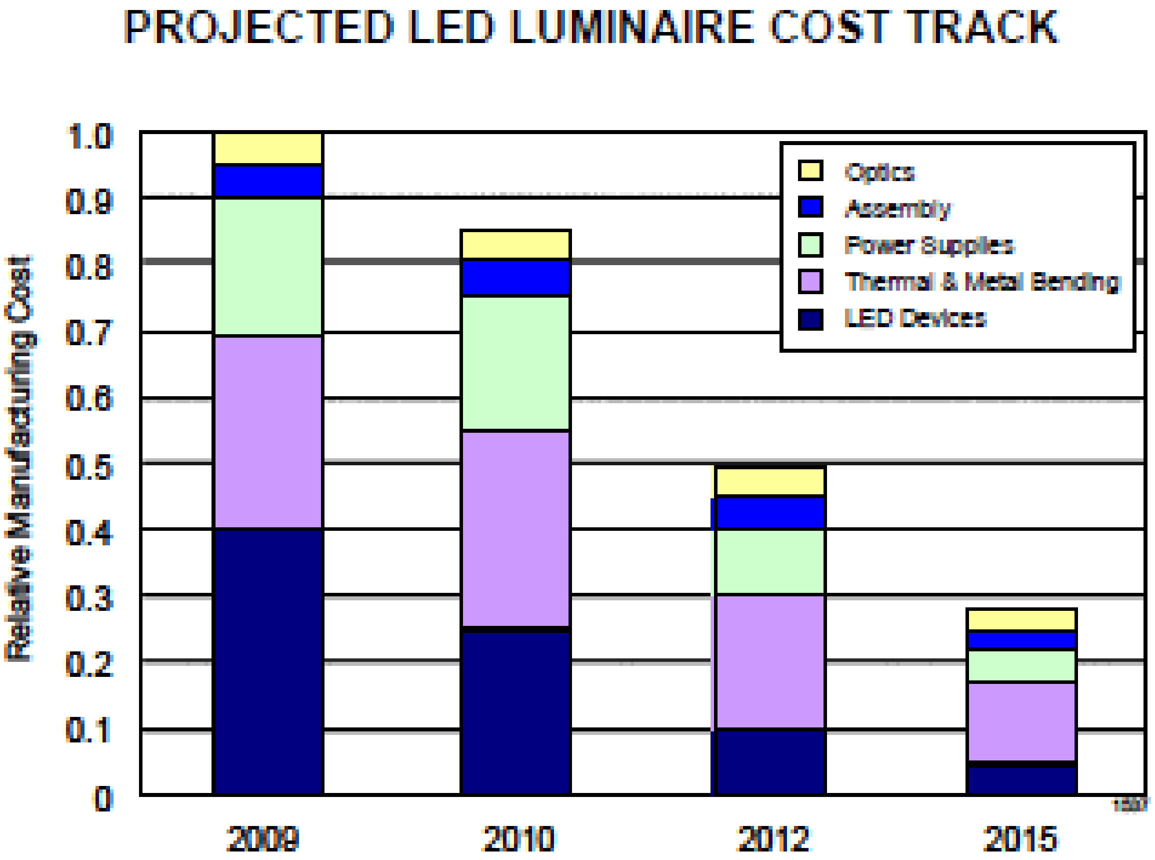
InGaN High Power LEDs Dominate



U.S. SUMMARY FORECAST BY MATERIAL AND PACKAGE TYPE
Revenues ($ Million)
2010–2014

Source & Courtesy Of: Strategies Unlimited

LEDs dropping from 40% to <20% of the Luminaire cost


PROJECTED LED LUMINAIRE COST TRACK

Source: DOE Manufacturing Workshop consensus.

Source & Courtesy Of: Strategies Unlimited

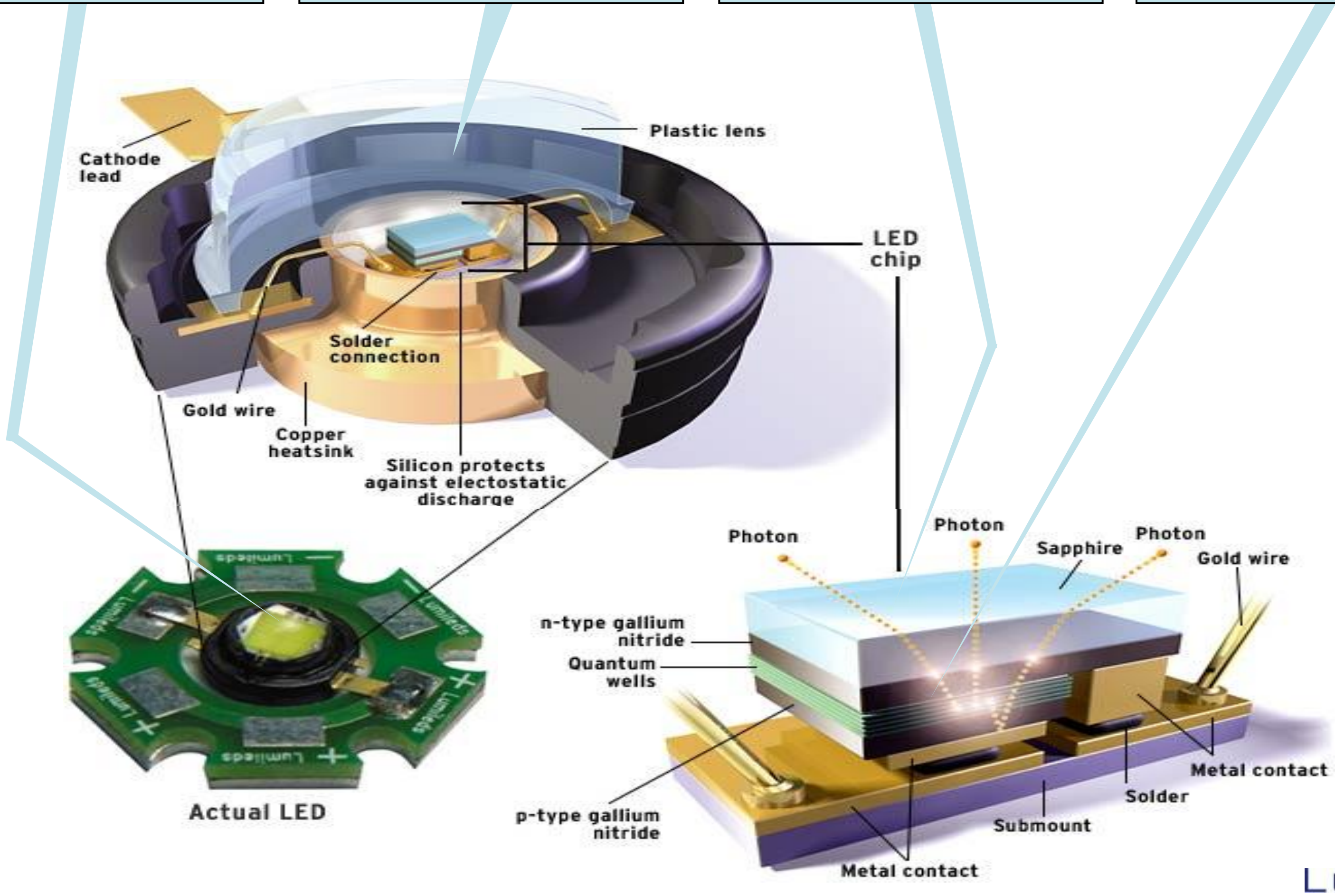
Target: LED adoption for general illumination

- ✓ Technology has crossed a performance threshold
  - ✓ >80 lm/W efficiency for “warm-white” LEDs
  - ✓ Specialized LED fixtures deliver system efficiency exceeding CFL levels
- ✓ The “Green” factor and legislation
- ✓ Cost of ownership
- ✗ First in cost

Analysis assumes 10 ¢/kWh, 8 h/day operation, and 90 % LED driver efficiency

840 lm Source	**Input Power**	**Source Cost**	**Energy cost per year**	**Source Lifetime**	**COO (one year)**	**COO (five years)**
60 W Incandescent	60 W	$0.30	$17.50	1,000 hr	$18.40	$92.00
17 W CFL	17 W	$2.00	$5.00	10,000 hr	$7.00	$29.00
Today’s 75 lm/W Warm White LEDs	12 W	>$12.00	$3.50	50,000 hr	>$15.50	>$29.50
Future 150 lm/W Warm White LED	6 W	$4.00 (?)	$1.75	50,000 hr	$3.75	$20.00

Elements of high-power LED technology



Phosphors

Package

Device (chip) design

Epitaxy and Materials

Luminous efficacy defined

η_L (Luminous Efficacy) =

The efficiency of a “white“ LED converting electrical power to light perceptible by the human eye

IQE (Internal Quantum Efficiency) X

EXE_n (Extraction Efficiency) X

ELE (Electrical Efficiency) X

This product is the Wall-Plug Efficiency (WPE) of a single-color LED

LE (Lumen Equivalent) X

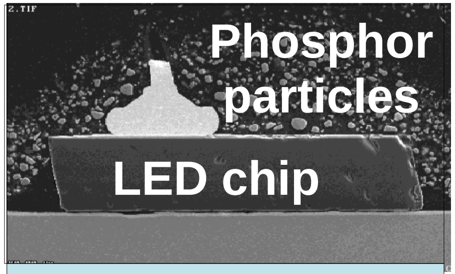
QEQD (Quantum Efficiency/Deficit) X

PE (Package Efficiency)

This product is often referred to as phosphor conversion efficiency

a short history of the WHITE pcLED

The white LED was born as a 5 mm LED with YAG:Ce^{3+} on top of a blue LED chip

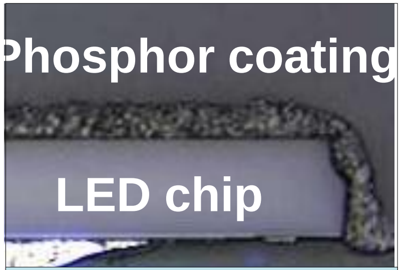


Conventional LED:

“Slurry deposited” phosphor particles

and you can still find some on the market, but **much has happened in the meantime …**

in a second generation – Luxeon®:



Luxeon LEDs:

Conformal phosphor coating

small source size retained

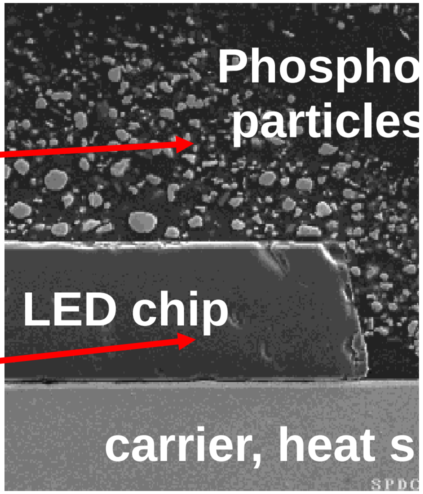
a significant improvement over slurries

different manufacturers of course have different packages

some drawbacks of phosphor slurries

over time LED efficiency AND power density increased, but thermal load too:

example: 1mm^2 chip
phosphor:
input = 0.6W
QE*QD = 0.7
waste heat 0.2 W
blue pump:
elec. input = 1W,
WPE = 0.6;
waste heat 0.4 W;



the heat conductivity of the resin, epoxy or silicone is about two orders of magnitude lower than the chip’s,
slurry gets hot,
organics degrade, brown, absorb, get even hotter, **degrade**
……

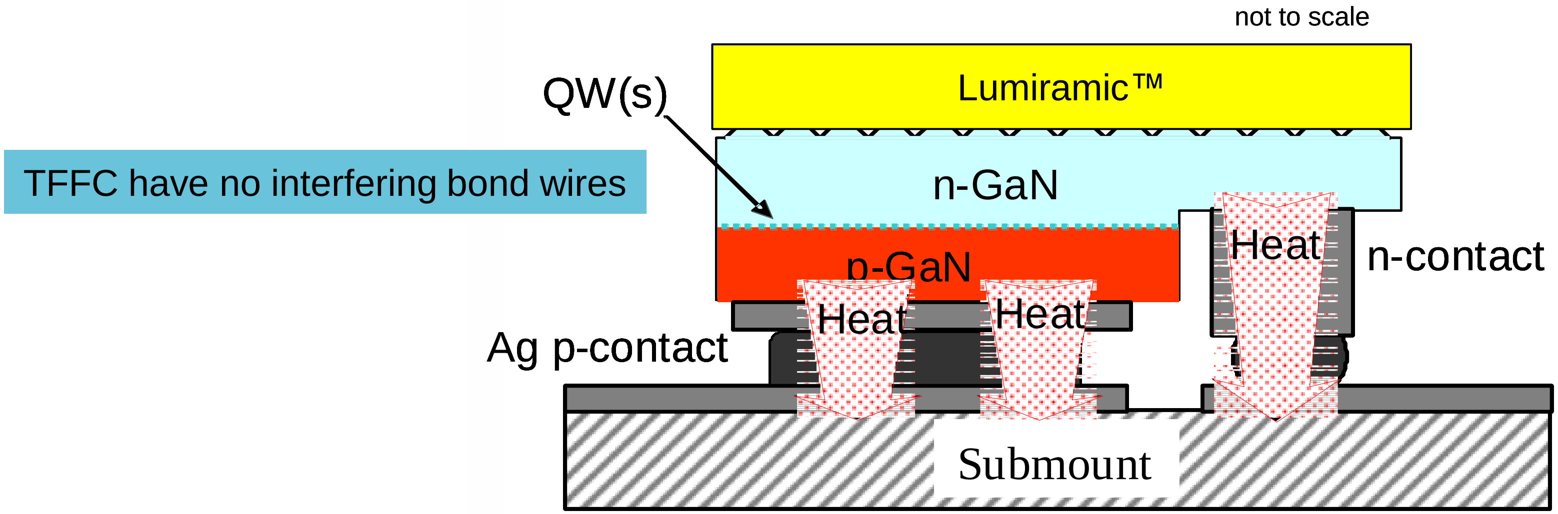
Phosphor particles in a different-index-resin scatter pump light and their own luminescence, If somewhere in the package is absorption, scattering means multiple absorption, dramatically lowering Package Efficiency.
A PE of 0.7 is fairly possible – 30% below optimum LOP !

consequence – reduce organics

LUMIRAMIC™

Lumiramic Phosphor Technology has been developed in Philips and is used solely by Philips Lumileds Lighting (PLL).

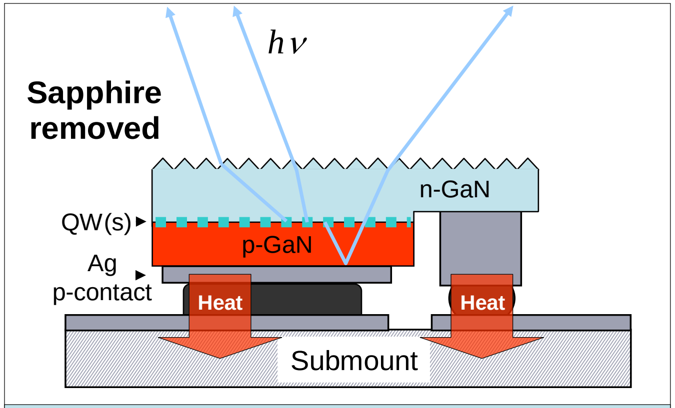
LUMIRAMIC™,
- it greatly simplifies the binning problem
- it reduces the amount of organic material in LEDs
- it allows to tailor optical properties, maximizing Package Efficiency
- it is perfectly matched to PLL's Thin Film Flip Chip (TFFC) technology



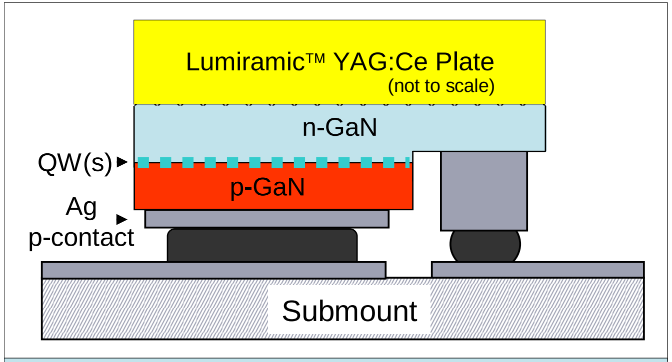
High-power LED technology

- Package
  - Low thermal resistance
    e.g., **Luxeon K2: ~5 K/W**
- Chip
  - Efficient heat extraction
  - High electrical efficiency
  - High extraction efficiency
    e.g., **TFFC LED: ~80 %**
- Phosphors
  - High conversion efficiency (lm/W_{opt})
  - High color rendering (CRI)
  - Imperceptible color variation (CCT)
    e.g.,**Lumiramic technology**

High power LED Technology



Thin Film Flip Chip LED



TFFC LED with Lumiramic™

How achievable is 150 lm/W, 1000 lm LED?

For single 1000 lm emitter,
2 A drive current needed

450-nm-pumped YAG:Ce pcLED,
4650K, 2 A, 1x1 mm^2

		Best Lab Result Today	Commercial Future
Internal Quantum Efficiency	IQE	53%	80%
Extraction Efficiency	EXE	90%	90%
External Quantum Efficiency	EQE	47%	72%
Forward Voltage (leads to ELE)	V_f (V)	3.4	3.3
Wall Plug Efficiency	WPE	39%	60%
Phosphor Conversion Efficacy	CE (lm/W_{opt})	228	252
Luminous Efficacy	η_L (lm/W)	90	150
Luminous Flux	ϕ (lm)	611	1000

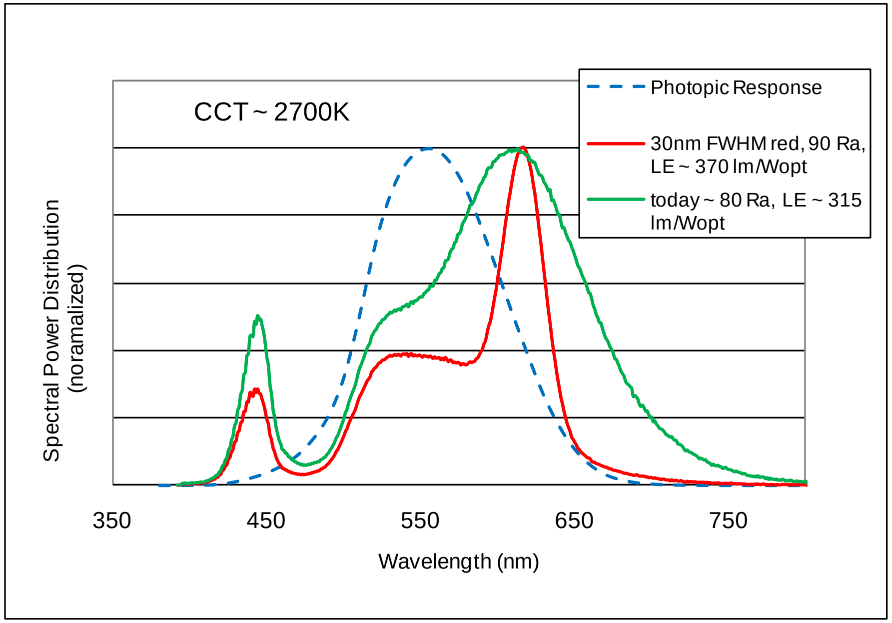
- High-current-density (~ 250 A/cm^2) internal quantum efficiency is critical
  - – Must increase by ~ 1.5 x
- Improved phosphor conversion efficacy is the other major area of focus

Challenge 1:
Narrow red phosphor for white LEDs

- Current red phosphors have broad emission (90-100nm)

- Substantial amount of light is emitted in far-red reducing lumen output, and also having limited benefit for color rendering

- Reducing the FWHM of red phosphor emission to 30nm can bring up to 20% increase in luminous efficacy of warm white LEDs



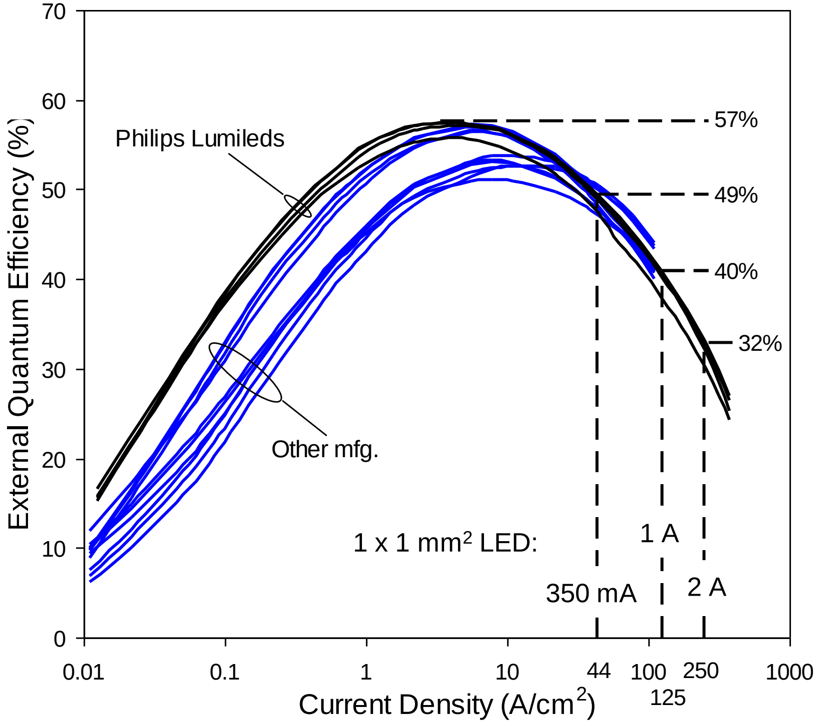
Options:

1. Quantum Dots (non Cd containing)
2. Novel inorganic phosphors
3. Novel organic phosphors

Challenge 2: “Efficiency droop” in III-nitride LEDs

- Large decrease of quantum efficiency as current density increases beyond ~10 A/cm^2 – “efficiency droop”
- Unique to III-nitride-based LEDs (blue, green, white)
  - AlInGaP (red, red-orange) LEDs exhibit much milder version, at much higher current density
- Fundamental problem for the whole industry
  - everyone’s LEDs & lasers exhibit this behavior
  - regardless of differences in details of mfg processes and device structures)
- Drives up the cost of ownership of LED lighting

Typical InGaN MQW Power LEDs

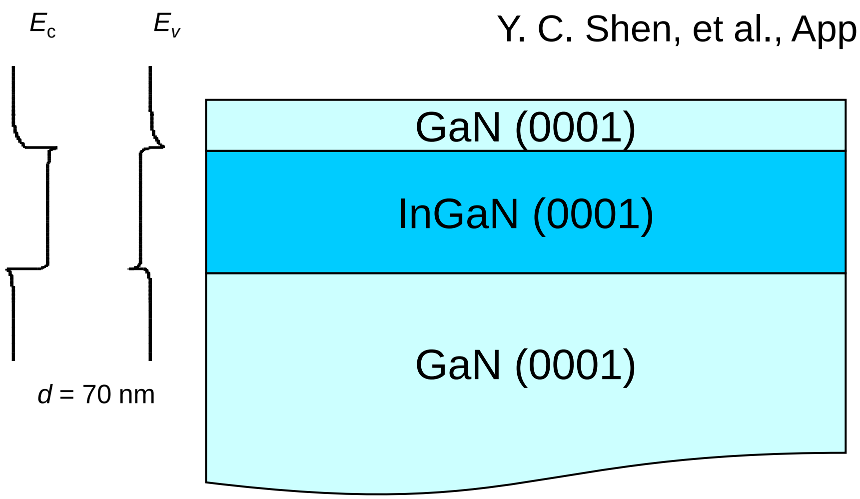


Hypothetical Explanations for the Droop

- nm-scale fluctuations in the atomic composition of the InGaN alloy light emitting layer
  - prevent electrons & holes from recombining non-radiatively at the ubiquitous threading dislocations, but can hold only so many carriers
- Electrons or holes “leak” out of the active region
  - because of ineffective confinement layers
  - because capture cross-section of quantum wells is small
- Electrons and holes are inhomogeneously distributed throughout the multiple-quantum-well active region
  - and distribution changes strongly with applied current
- Auger recombination hypothesis led by Philips Lumileds
  - gradually gaining acceptance in the scientific community as the best explanation

Measuring Recombination Coefficients—PL fitting

Y. C. Shen, et al., Appl. Phys. Lett. **91**, 141101 (2007)



$$\eta_{\text{int}} = \frac{R_{rad}}{R_{total}} = \frac{Bn^2}{An + Bn^2 + Cn^3}$$

A = Hall-Shockley-Read non-radiative (s^{-1})
B = radiative ($cm^3\,s^{-1}$)
C = Auger non-radiative ($cm^6\,s^{-1}$)

Samples:

- Grown by MOCVD on different *c*-plane templates:
  - GaN on Al_2O_3 (TDD~5×10^8 cm^{-2})
  - ELOG GaN (TDD~2×10^7 cm^{-2})
- InGaN is pseudomorphic
- Quasi-bulk InGaN, t > 10 nm
  - Results in flat bands

Assumptions:

- 100% injection efficiency (true for resonant PL excitation)
- *n* = *p*
  - Accurate for active region doping $< 1 \times 10^{18}$ cm^{-3}
- *B* is independent of *n*

Implication

- Auger coefficient $C \sim 1.4 - 2.0 \times 10^{-30}$ cm^{6}s^{-1} in quasi-bulk (10 - 77 nm) $In_xGa_{1-x}N$ layers with $x \sim 0.09 - 0.15$

- Auger recombination rates are significant in InGaN for $n > 10^{18}$ cm^{-3}

- Typical operating conditions for InGaN LEDs : $n \sim 5 - 10 \times 10^{18}$ cm^{-3}

- Auger recombination is the dominant cause for efficiency “droop” in all state-of-the-art commercially available visible-spectrum InGaN-GaN LEDs

- Knowledge of this limiting mechanism → new active region designs to reduce carrier density and increase η
  - Double-heterostructure is one example

Approaches to Reducing Droop

- Reduce polarization-induced electric fields (according to the carrier distribution hypothesis and the carrier leakage hypothesis) in the active region by
  - replacing GaN barriers with InGaN or AlInGaN
  - replacing AlGaN electron blocking layer with AlInGaN
  - using a substrate which gives an active region grown in a non-polar or semi-polar crystallographic orientation (such as (100), (201), (112), etc.)
- Tailor the electron and hole distribution in the active region
  - dopants in the active region
  - complicated quantum well designs, superlattices, etc.
- Double-heterostructures
- Reduce threading dislocations and other defects (bulk or quasi-bulk GaN substrates, optimized deposition conditions for the active region)

Summary of Challenges

- Goal of 1000 lm/$ for Illumination requires solutions to:
- Challenge 1: Reduce the FWHM of red phosphor emission to 30nm can bring up to 20% increase in luminous efficacy of warm white LEDs
- Challenge 2: Improve droop to meet High Current Density (~ 250 A/cm^2) IQE improvement by a factor of~ 1.5 x
- Requires fundamental new materials development, industrialization and volume deployment within 4 years.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