Lighting Technologies

Research, Innovation, & Engineering
M. Nisa Khan
Red Bank, New Jersey

How Can Quality LED Lighting Win in Energy Efficiency and Cost Competition?

October 9, 2014

TOPICS

PART I

- What is “lighting quality”?

(intensity, color, 3D intensity distribution)

- Quantification necessary

PART II

- What impedes lighting quality?

(glare, color distortion, unnatural 3D-LID)

- Glare? (ex. of lamps)

PART III

- Why is LED binning a headache?

(LED Manufacturing Challenges)

PART IV

- Are there winning <u>solutions</u> for low-cost & energy-efficient <u>high-quality</u> LED lighting?

PART I: Defining Lighting Quality

Quality lighting: creating illumination with the right intensity and color balance in 3-dimensional space.

Lighting Quality Specification - Application dependent

- Everyday lighting: task-oriented, merchandising, comfort setting (home, restaurants, etc.), or nighttime outdoor lighting
- Entertainment lighting: outdoor jazzy events, sports arenas, theatre, etc.

→ Discussions will apply to all lighting to some extent; but specifically to:

- **Light intensity (range: high/low);**
not just at a point or plane, but full 3-D spatial distribution

- Color (fidelity, temperature, spectral ranges,…)

Lighting designers create good lighting in environments

Good lighting is recognized by most

Illumination engineering and lighting design is a process

Process: Quantify light parameters → corresponding to light quality

(e.g., LID, CRI, CCT, …)

Well understood and established, but -

More in-depth quantification is necessary

in the advent of **LED lamps**

In the advent of LED lamps, in particular →

- Lighting industry – separated from the display industry
- Lighting industry – needs luminous intensity
  (provides description for illumination in space)
- Display industry – needs luminance
  (provides description for surface brightness)

While practical, a conceptual problem was generated:

Many in the lighting industry – appear to believe

Luminous intensity and luminance are two disjoint parameters

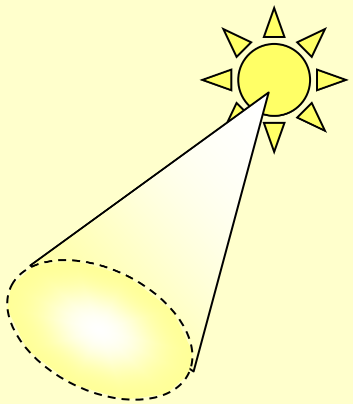
BUT - Luminous Intensity and Luminance are <u>NOT</u> disjoint parameters.   Why not?

Someone with a different background – says you need to measure Luminance for lighting → misunderstood?

While "Lighting" is surely an art and subjective, it is also invariably subjected to Physics!

- Stress our understanding level of measurements and calculation
- Luminous intensity cannot be directly measured with a meter
- Why not?

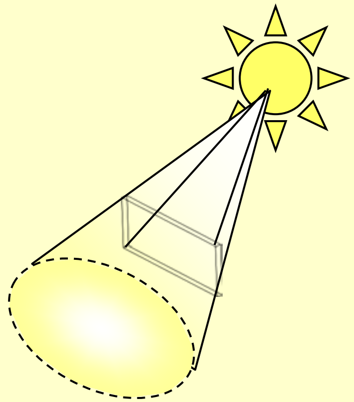
Luminous Intensity



Lumen/str.

Cannot be physically measured

Luminance

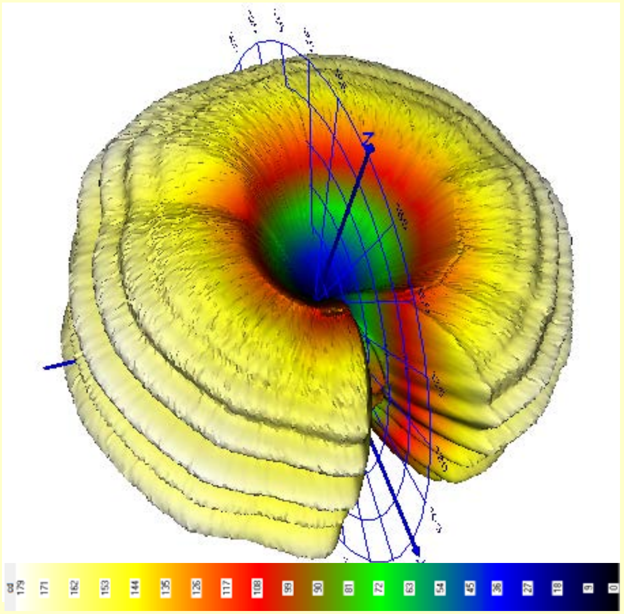


Lumen/str./m^2

Can be physically Measured

(source property if measured off the source)

Luminous Intensity Distribution



Cannot be physically measured

But is entirely calculated from all measured quantities

(luminance, total flux, source size, distance between source & detector, and other physical measured parameters)

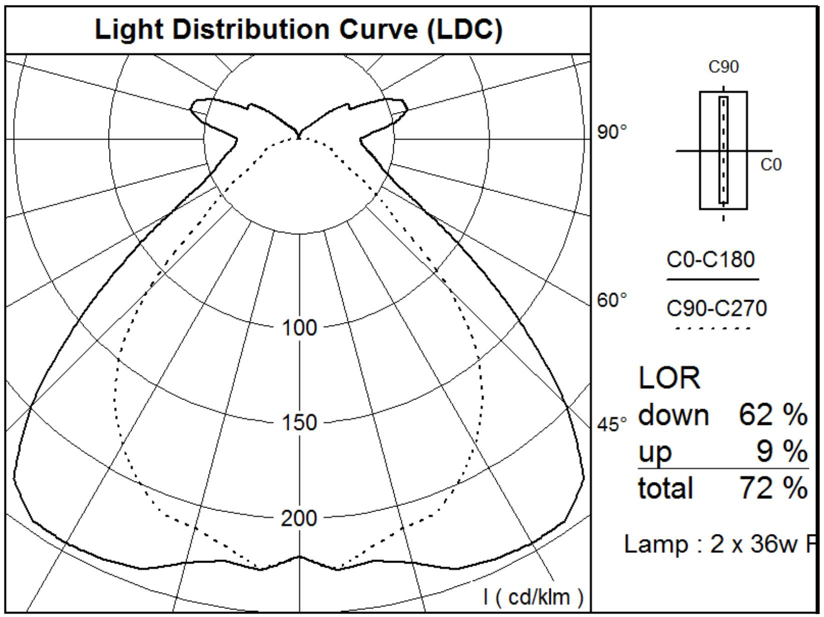
We can only measure finite quantities

Quality Lighting Parameters

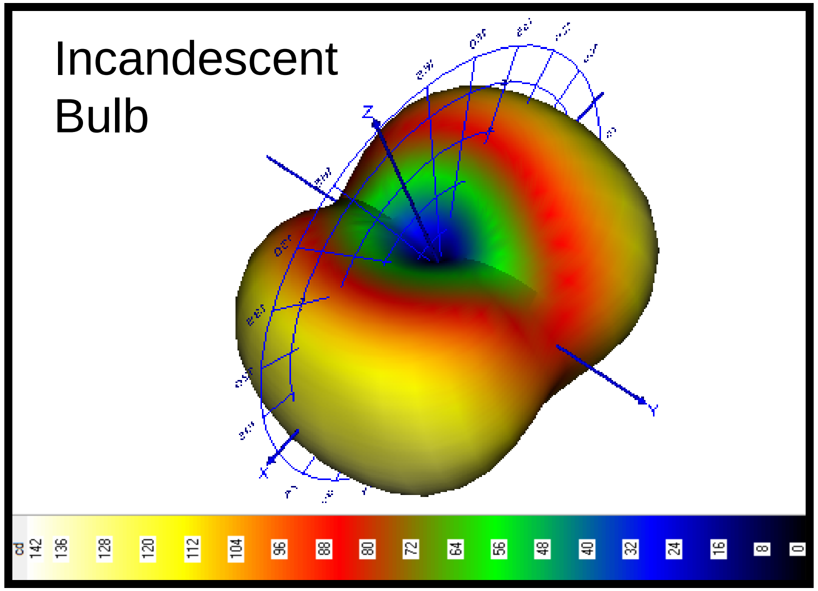
- Luminous Intensity Distribution **(LID), L and CRI, CCT** or other
  - LID gives candela in (*x,y,z*) – light and shadows
  - CRI gives color fidelity – spectrum dependent
  - CCT gives color warmth – spectrum dependent

2D is OK; 3D most helpful

2D-LID



3D-LID



LID, L, CRI, CCT - give the information lighting designers need to create “quality lighting”

Luminous Intensity and Luminance are NOT disjoint parameters

- LID is calculated from measured luminance or illuminance
- Luminance and LID are both important for SSL
- Luminance - level, range, uniformity

PART II: Impediments for Lighting Quality

Bad lighting: creating illumination with too high/low intensity or color distortion in space.

If luminous intensity or luminance too high → Glare is generated

Glare can cause color imbalance

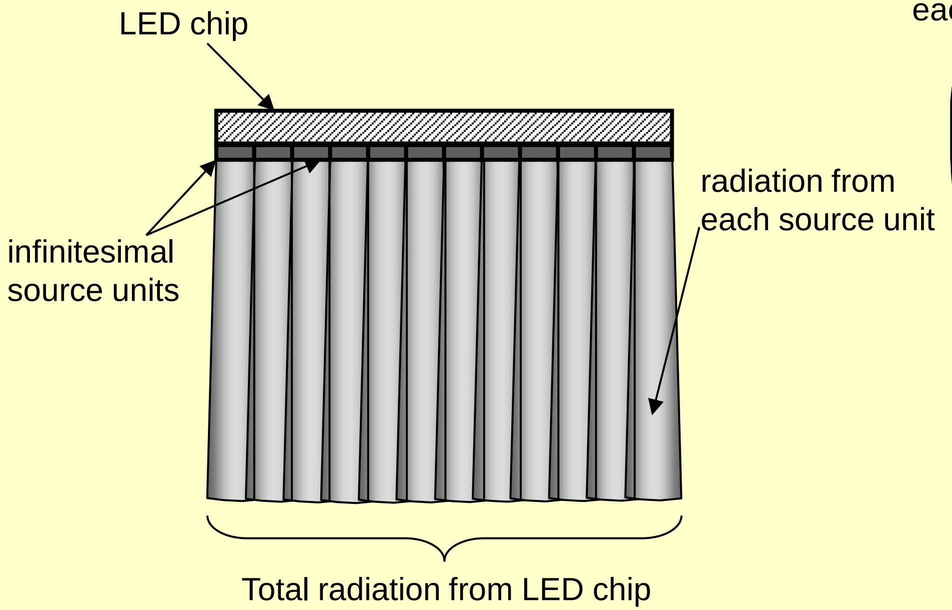
What is Glare? (UGR, CGI, BGI, VCP, …)

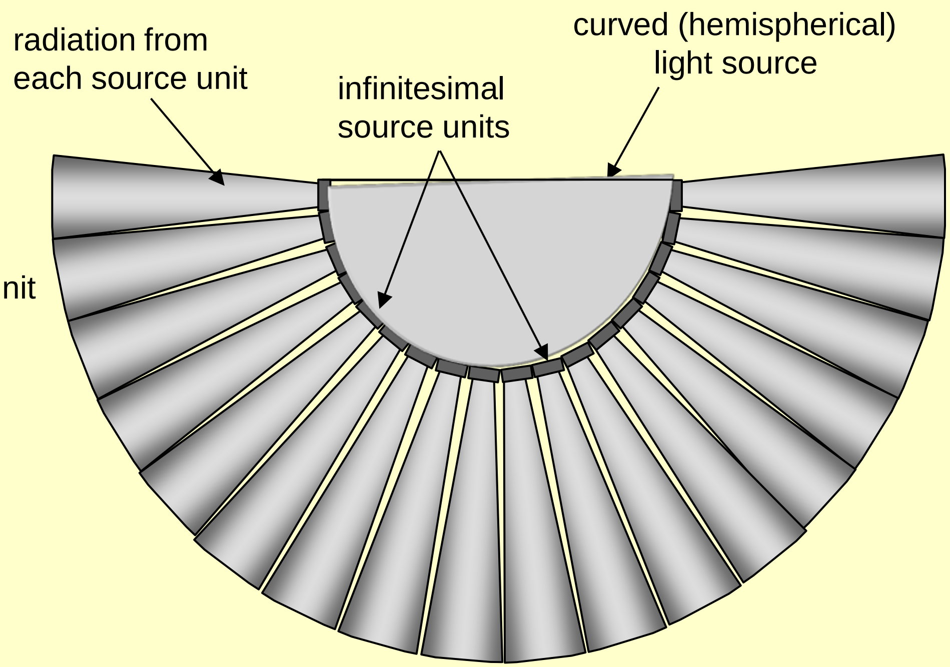
Unified Glare Rating: Simplified and consolidated CIE definition

$$UGR = 8\log\left[\frac{0.25}{L_b}\sum\frac{L_S^2\,\omega}{P^2}\right]$$

What causes certain light sources to have high luminance?

Scientific Explanation – Why LED's Produce High Glare

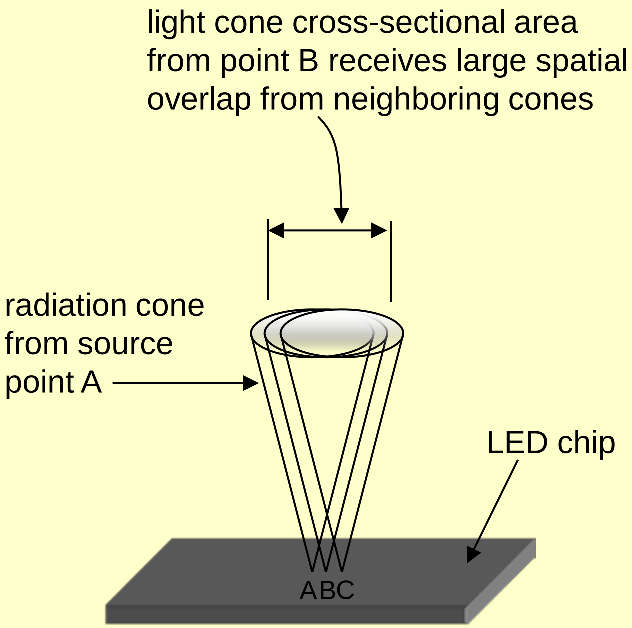




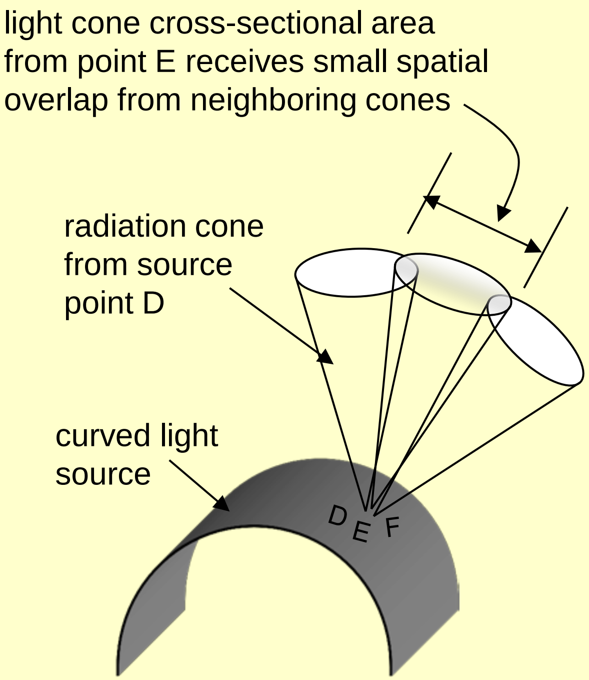
the radiation is only emitted normal to the LED chip surface as governed by the *Divergence Theorem*

The radiation is only emitted normal to the curved surface as governed by the *Divergence Theorem*

Quantitative Explanation – Why LED's Produce High Glare



(a)



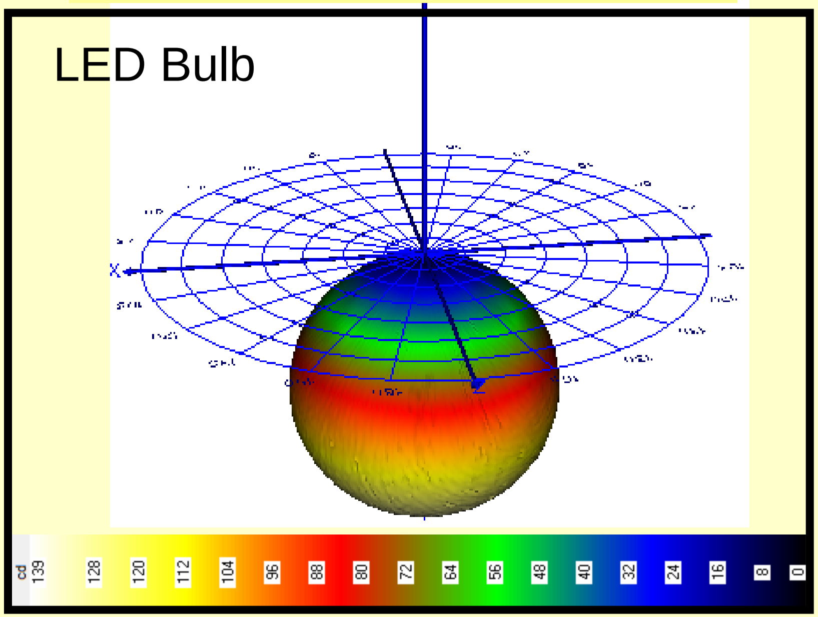
(b)

DIVERGENCE THEOREM: $$\iint\limits_S \vec{F} \cdot \vec{n} \, dS = \iiint\limits_V \vec{\nabla} \cdot \vec{F} \, dV$$

Quantitative Explanation for LID Profiles

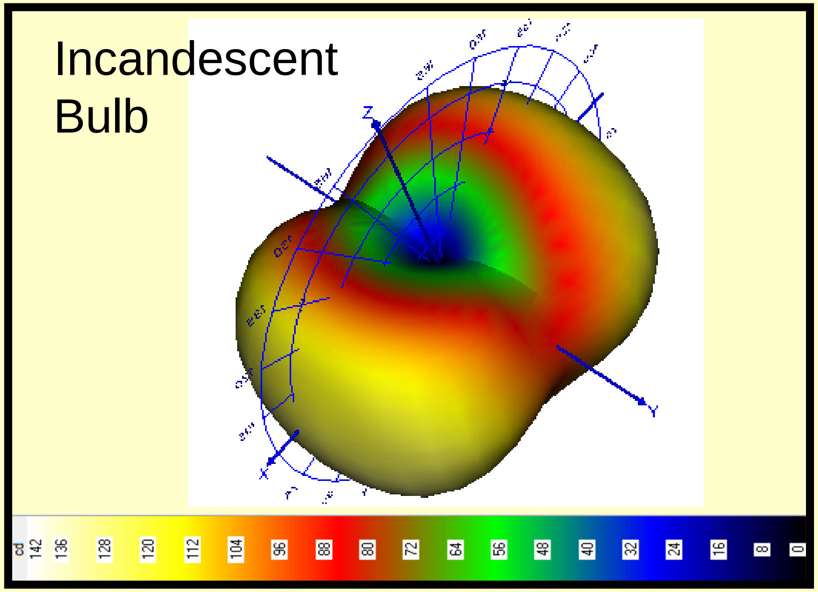
LEDs Produce Lambertian LID

Determined via measurement



Curved Lamps Produce Non-Lambertian LID

Determined via measurement



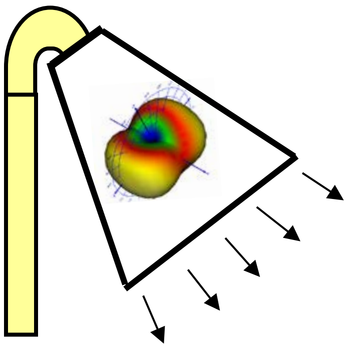
Can you see why LEDs produce high glare?

LID from LED Complicates Lighting Design

Form has played a big role in lamp and luminaire design with traditional lamps

Reason?
Macro technology
→ LID can be affected with form

→Tailor LID to suit needs by lighting design



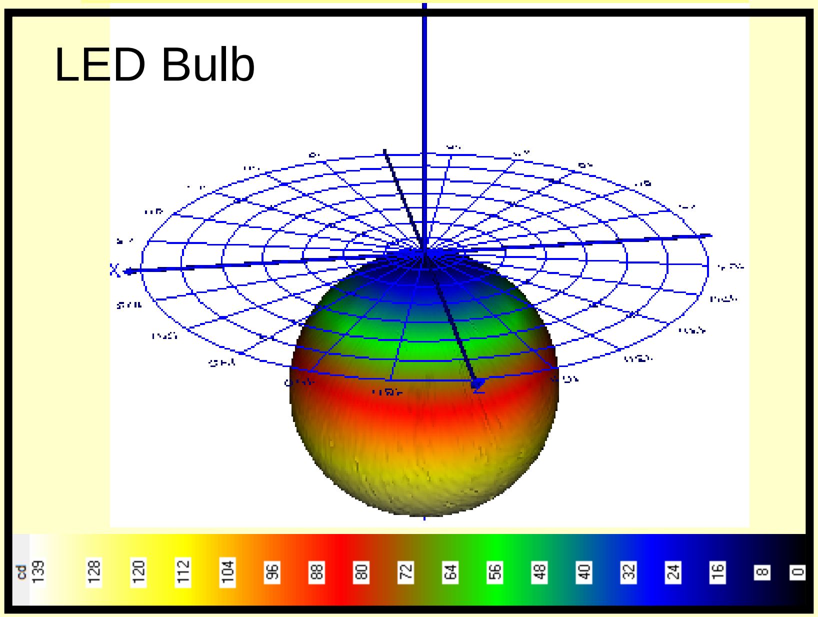
With LEDs? **Form is not functional**

Why?

LID out of a single or arrayed LED modules → still Lambertian

Lamp Examples Showing Unnatural Illumination

Determined via measurement



1.G12 132smd2835: **DC12V,15W,1400 Lumens**

2.G12 70smd2835:**AC100-240V,10W,1080lumens**

Examples of Natural & Unnatural Illumination

Natural Illumination

LID – adequately homogeneous

Unnatural Illumination

(Used all LED lamps)

LID – lacks adequate homogeneity

LED Lamp Examples to Cause Unnatural Illumination

All these LED lamps/luminaires – produce "Lambertian-like" LID – not suited for the desired applications

LED Lamps Causing Unnatural Illumination

Illumination lacking homogeneity

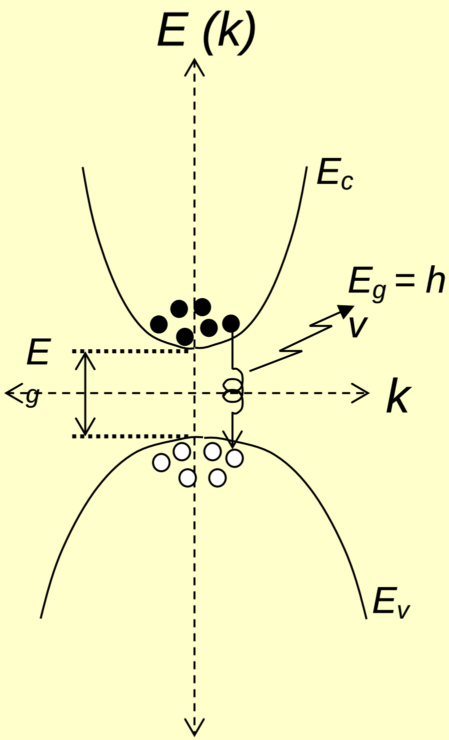
PART III: LED Reliability & Reproducibility

LED lamps – Quality Variation is Inherent

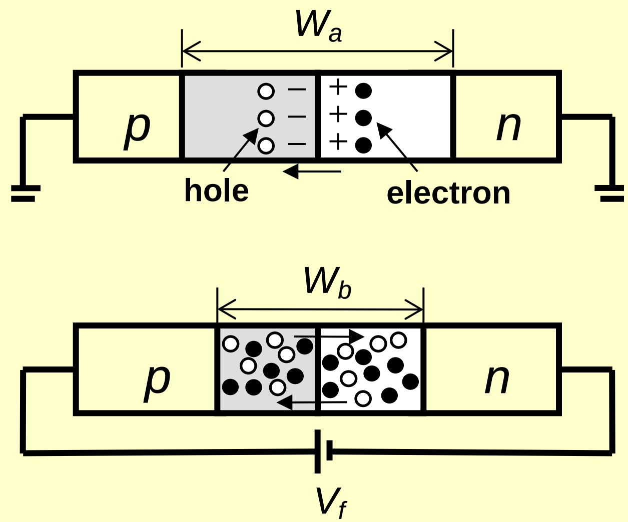
LED efficiency comes from basic compound semiconductor properties:

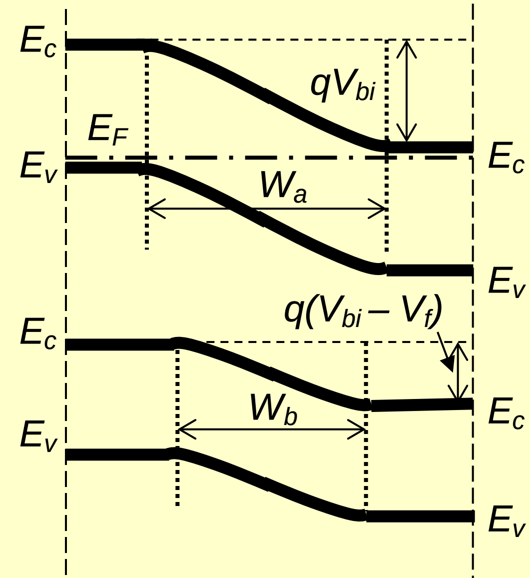
- Small region in a material where electrons-holes from current can generate light
- Comes with challenges: material has defect sizes on the order of light wavelength → light generation efficiency varies greatly
- Material composition (AlInGaP, AlInGaN) variation → color shift
  - Efficiency depends on what material is used (red is better)
  - Efficiency depends on how much current is injected
  - Efficiency depends on keeping the material temperature low

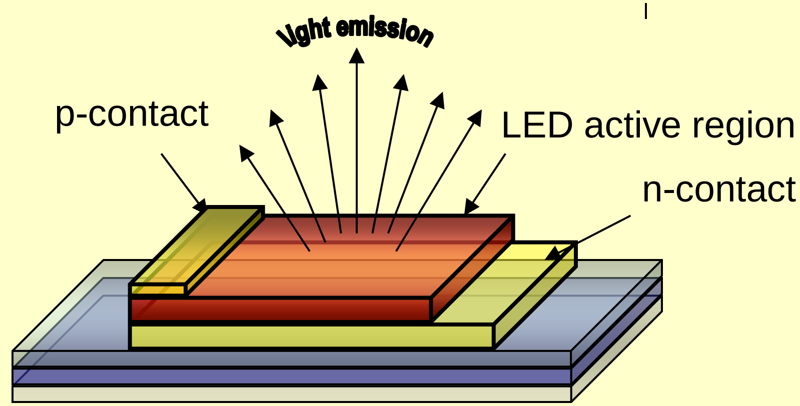
LED Operation – Qualitative Description



Energy Diagram of Direct Bandgap Semiconductor

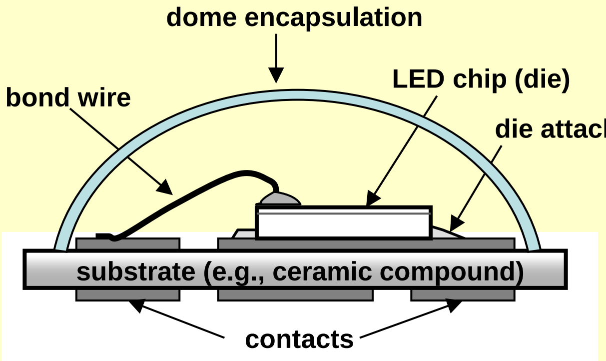


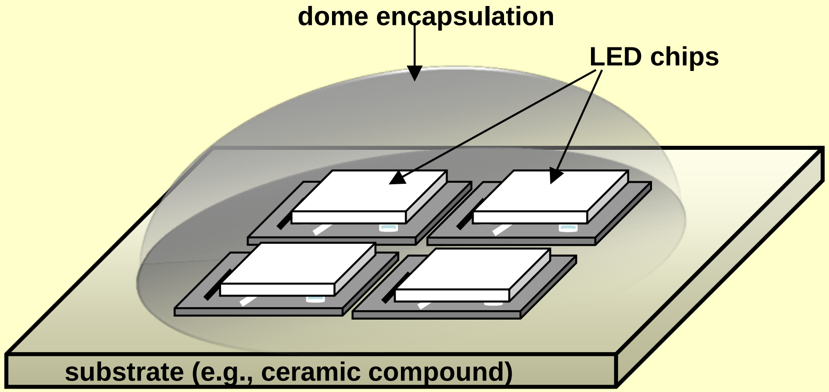




Color and efficiency binning, AND glare – inherent challenges

LED Light Source – Construction Details





- LED chips generates heat
- Heat must be removed
- Heat sink design must be effective

Understanding Reliability and Reproducibility

Reliability: Are operation and lifetime dependable?

- Design and manufacturing
  tolerance, control, verification

[fab, packaging (wire bonds, boards, heat sink, lens, etc.]

Reproducibility: Can the same module be remade?

- Design and production
- Wafer level issues (more challenging)

- R&R contribute to binning/wide variations from a slew of manufacturers.

Very reliable and reproducible LED modules → available at high cost

PART IV: High-quality, Energy-efficient LED Lighting Solutions at Low-cost

Why is Energy-Efficient Lighting Important?

More wattage, more CO_2, …

Why is Quality Lighting Important?

Artificial light: best when mimics natural light
(mimic not just in color, but also in LID)

<u>LED light may cause:</u>

- Circadian rhythm disturbance
- Blue light hazard
- Nausea
- Seizure from dot patterns, stroboscopic effects
- Discomfort from glare

Problem Definition: Obtain High-Quality, Energy-Efficient LED Lamp at Low Cost

Lamp Characteristics

- Glare-free
- Luminous intensity distribution:
  - with suitable min, max, and profile
- Flicker-free
- Good CRI, CCT
- High lumen/W
- Uniformity
- Minimize lumen depreciation
- Performance over time
- Long lifetime

Adds cost

How to Lower Cost?

How to lower cost?

Integrated Design & Development Approach

- Research
- Technology
- Tools
- Analytical and holistic approach
  to problem identification and solving
- Vetting
- Inspiration

What to Avoid

- Contradiction
- Short-term solutions
- Inaccurateness in --
  - Focus
  - Misidentifying problems
  - Incomplete models
  - Incomplete check lists

SSL Solutions for High-quality and Low-cost

External Package Resemblance – Not Sufficient

Concerns

- Glare; non-gradual LID
- Poor heat dissipation
  → low lifetime

Claims

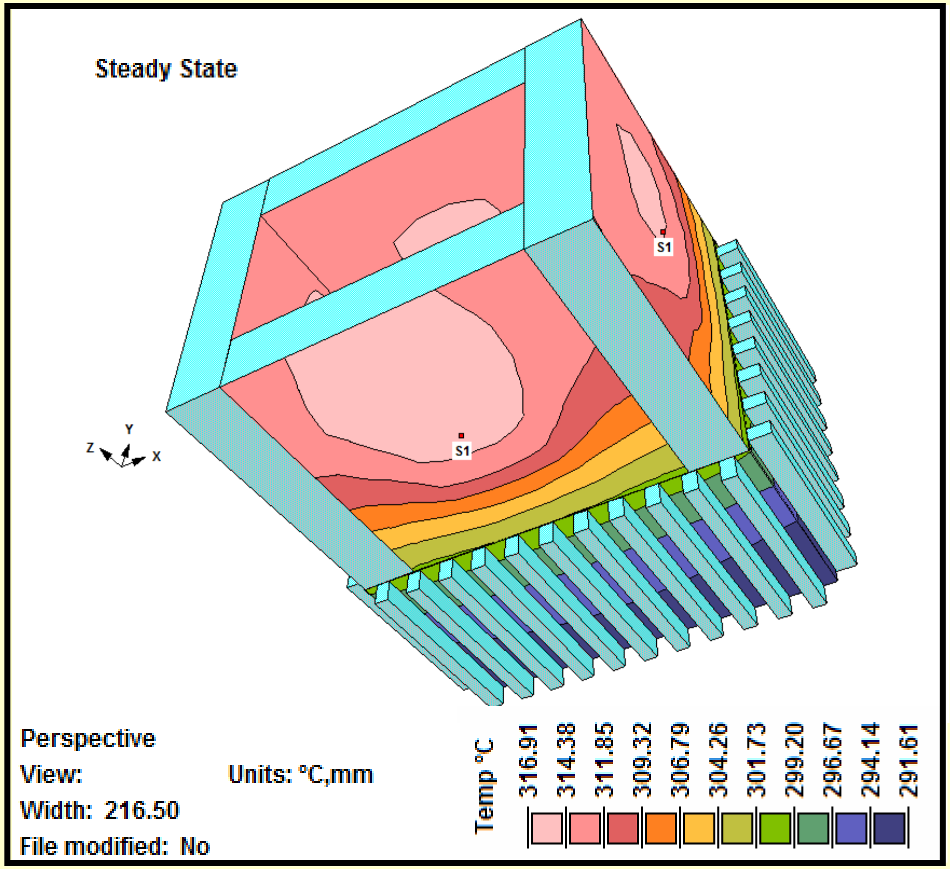
High efficiency
360 Ceramic
Bulb at low cost

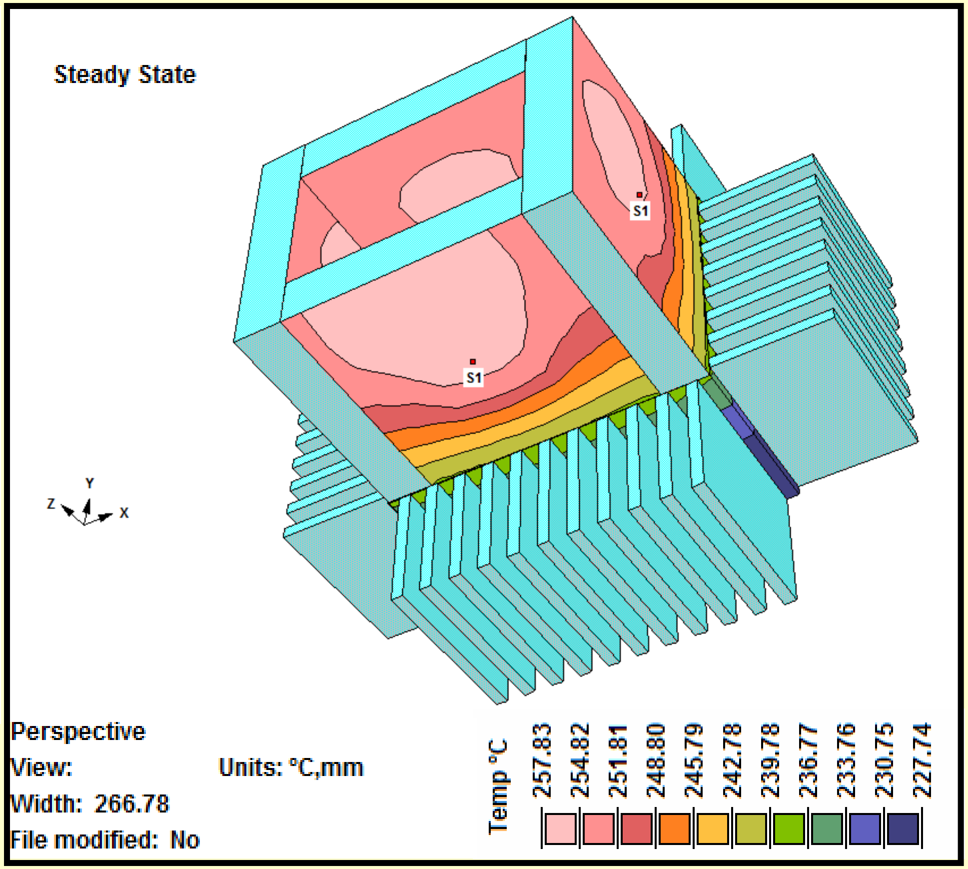
How to lower cost? ⇒

Relevant Areas:

Optics
Thermal
Electrical
Mechanical
Test/Verification/etc.

Thermal Design Matters

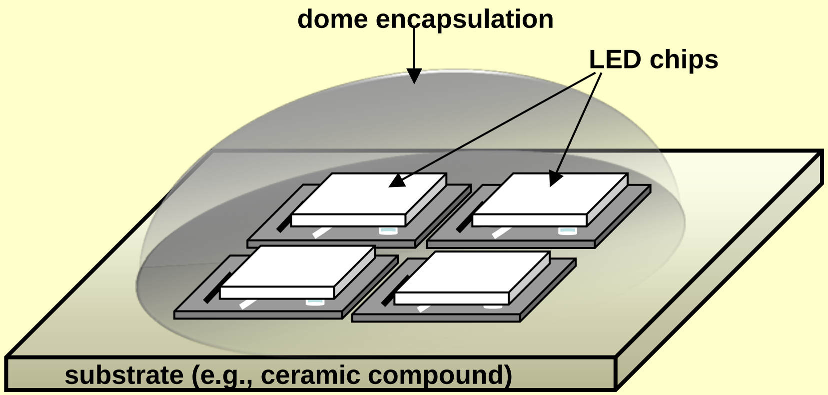




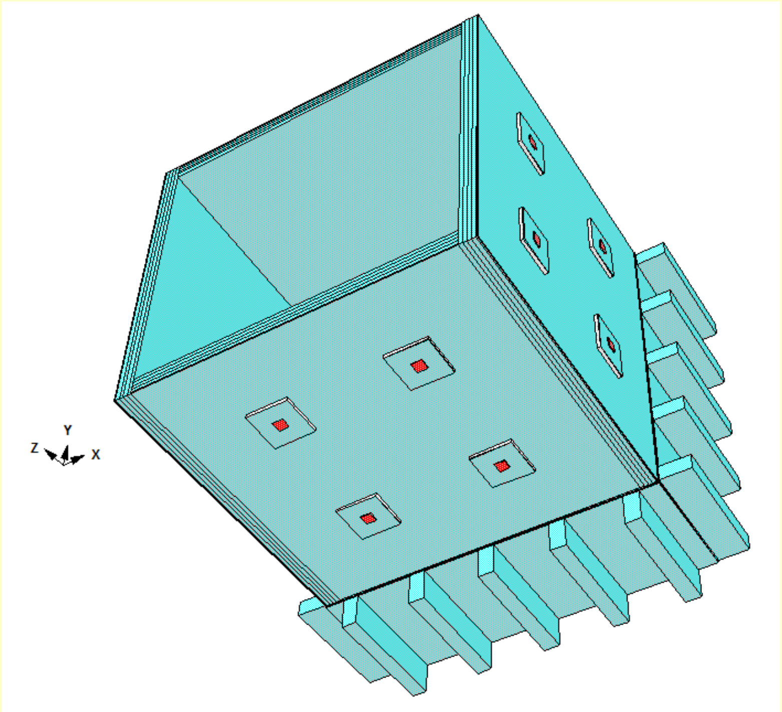
- **Thermal management comparison with a 40W power transistor device on each vertical board**
- **Short fin model is 59 deg. C hotter!**

Mechanical Design Matters

LED Modules on a Single Board



LED Lamp Engine with Multiple Boards



Mechanical Design:

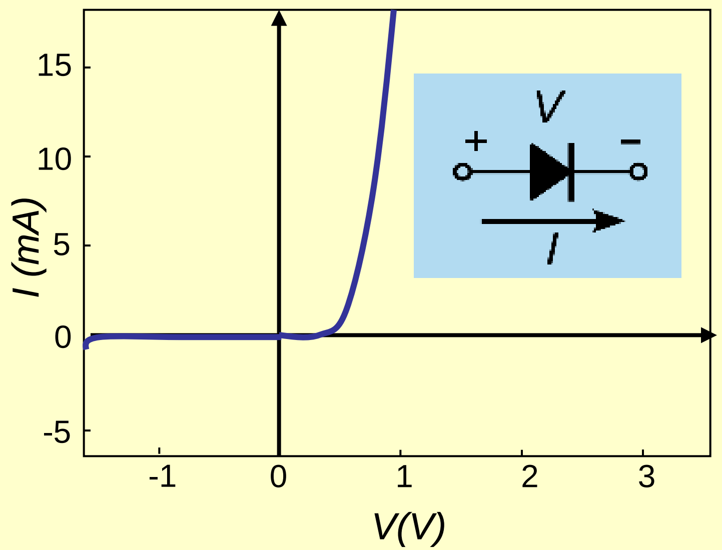
- Thermally effective
- Lighting performance
- Durable construction
- Orientation agnostic – common usage

End-end integration:

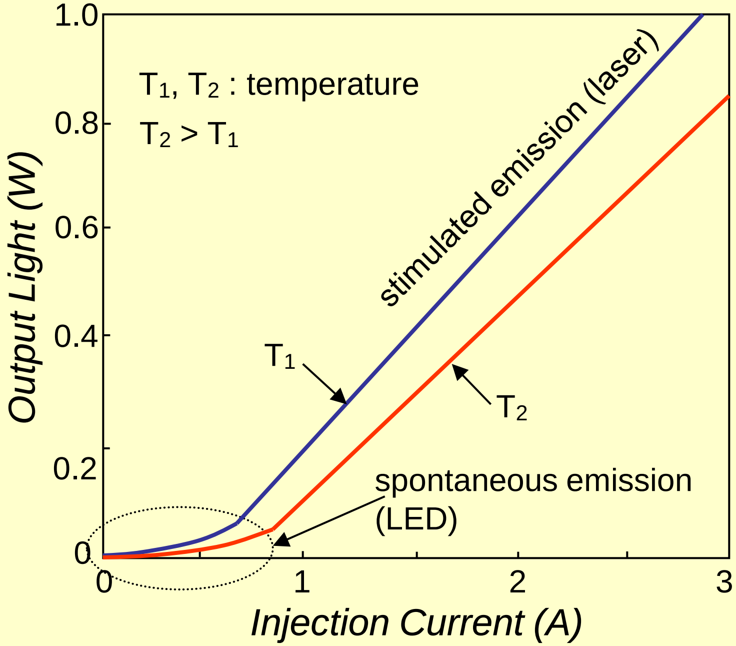
- Boards, substrate, heat-sink
- Electrical main
- External capsule

Electrical Design Matters

LED *I* - *V* Curve

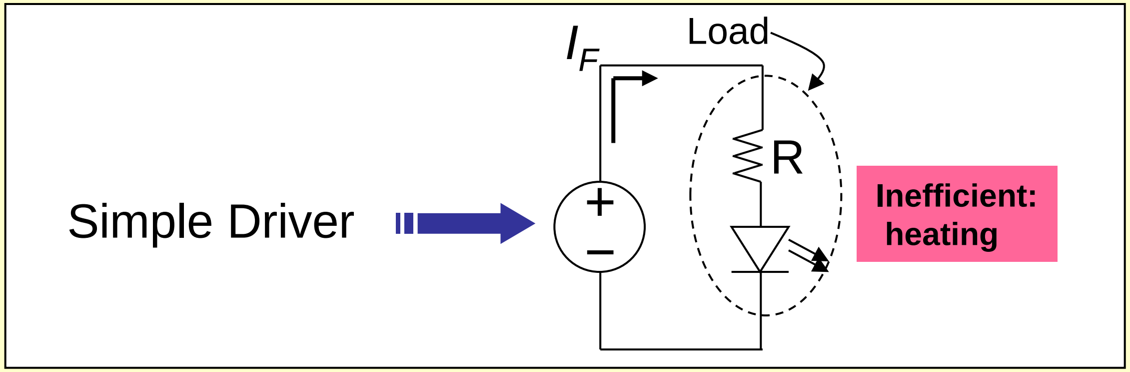


LED *L* - *I* Curve

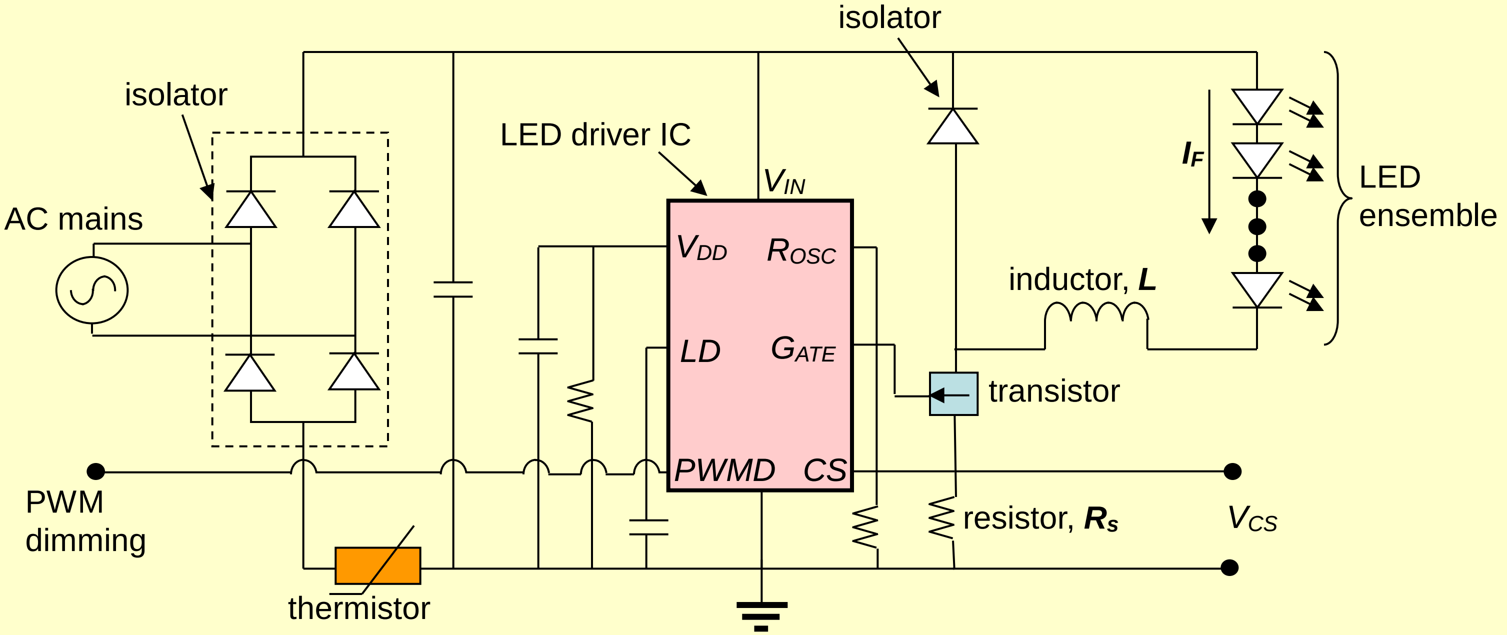


- Applying V_f or I_f produces *L*
- I_f is better, *L* is linear
- I_f must be limited <u>and</u> constant

Electrical Design Matters



Need a Constant-Current Driver CKT



- IC for boost, buck, buck-boost, SEPIC, flyback to control I_F
- Comparator Ckt (V_{CS}, R_S) monitors I, adjust D_{PWM}
- C_{ext} selects f
- P_{eff}, P_f – non-ideal
- Thermal concerns (IC, R, transistors, LED)

Optical Design Matters

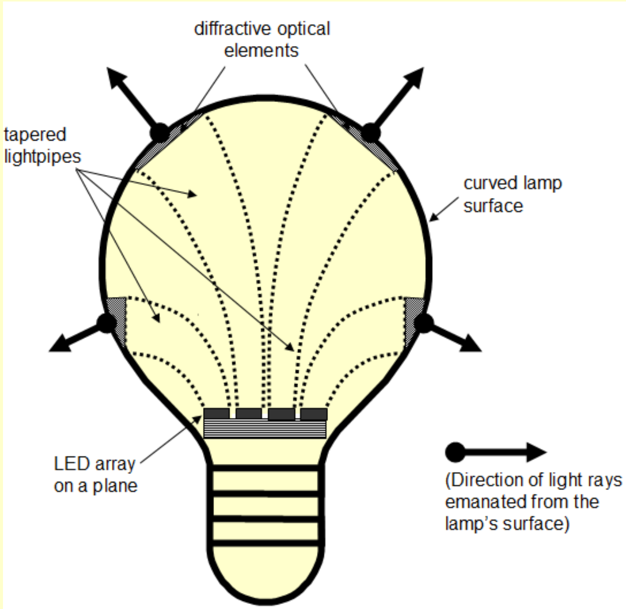
External Package Resemblance – Not Sufficient

CLAIMS:
High Lumen: The 3.4W version LED filament bulb can reach 400-450Lm which can replace the 40W incandescent bulb completely.

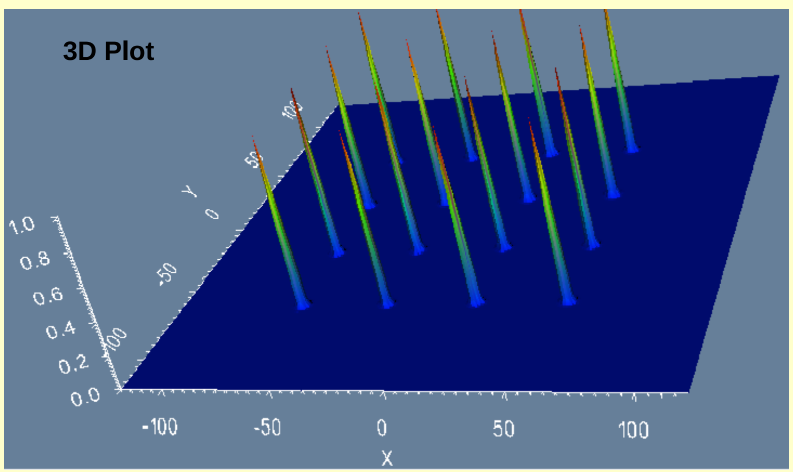
CLAIMS:
Perfect lighting performance. Our filament LED bulb bean angle is 360deg which is same with the incandescent bulb.

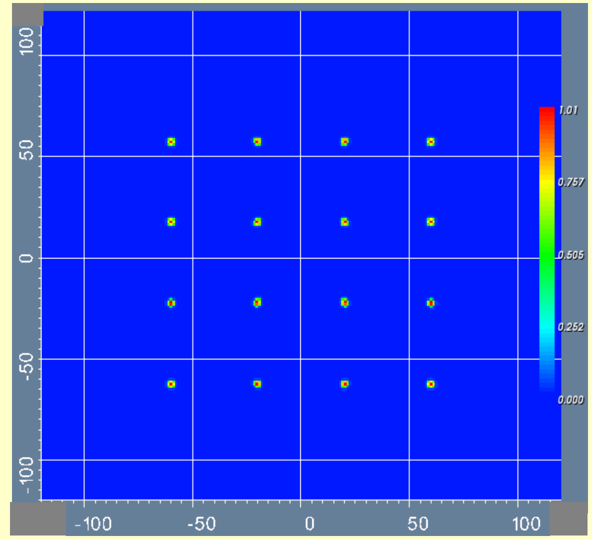
INCORRECT!

LED Light Source – Large-scale, 3D Illumination – Patented Solutions

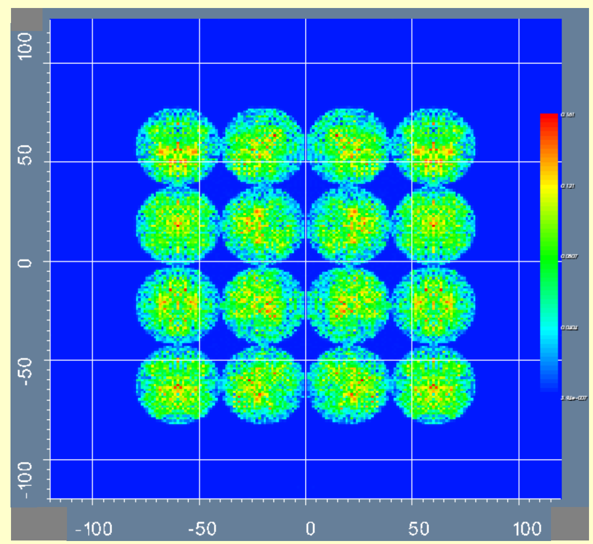


Patented LED Bulb (Khan's US. Patent & more pending)



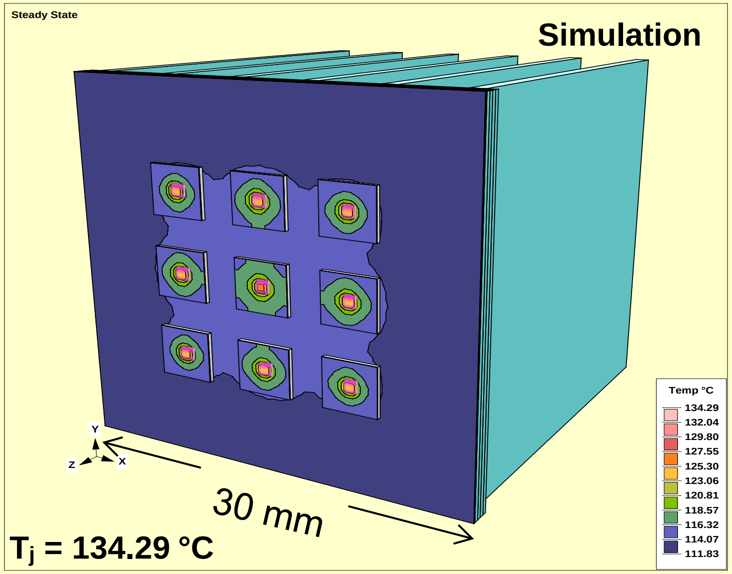


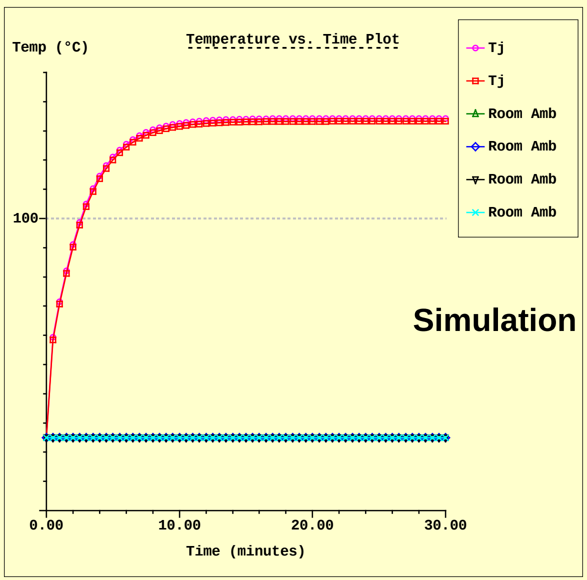
Optical Simulation (without taper in fiber/waveguides/ light-pipes)

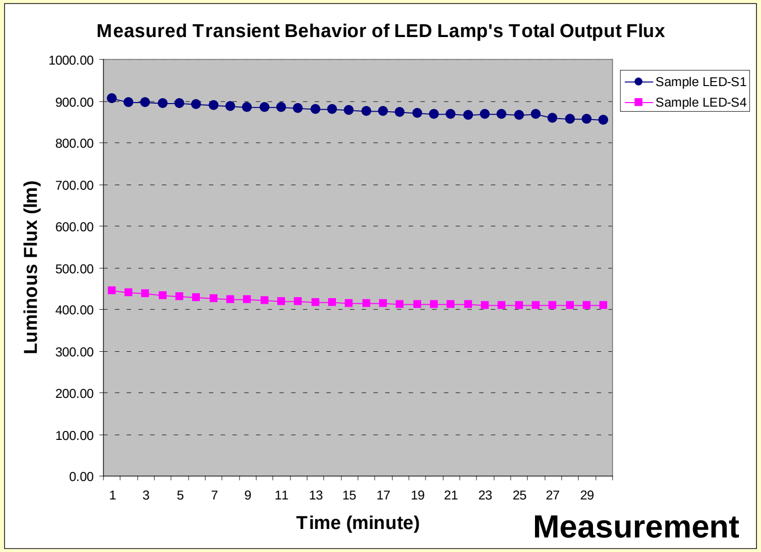


Optical Simulation (with taper in fiber/waveguides/ light-pipes)

Test & Verification Matters







*Simulation & measurement agree on time required to reach steady state for LED bulb (LED S4)

SSL Solutions for High-quality and Low-cost

Thermal, mechanical, optical, electrical design and production → interrelated!

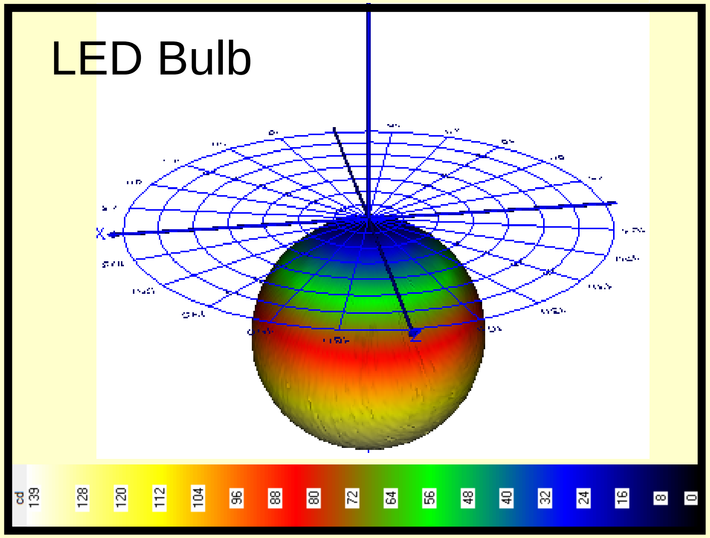
Design optimization – necessary for each application

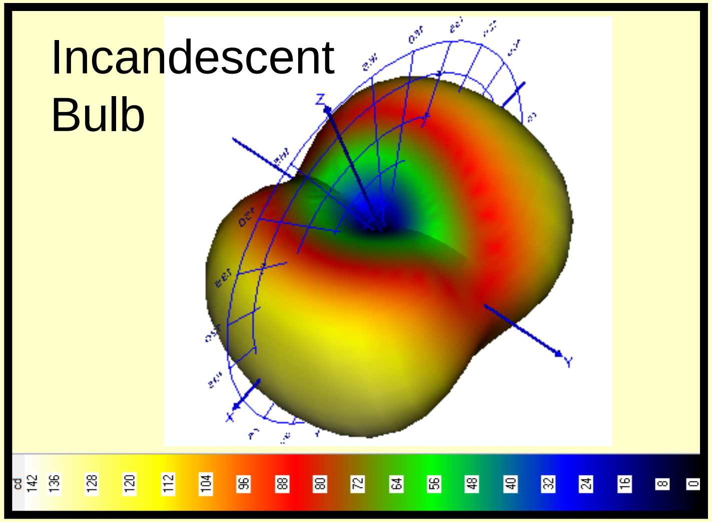
Major challenge: batch testing for optoelectronics, i.e., SSL lighting products!

Conclusions and Future Projections

Conclusions:

- Lighting quality: Color and 3D intensity distribution
- Glare impedes lighting quality in LEDs
- Quantification: Luminous Intensity vs Luminance
- Luminance: glare and LID
- Binning concern: unique for SSL lighting
- Yes – winning solutions exist; implementation next





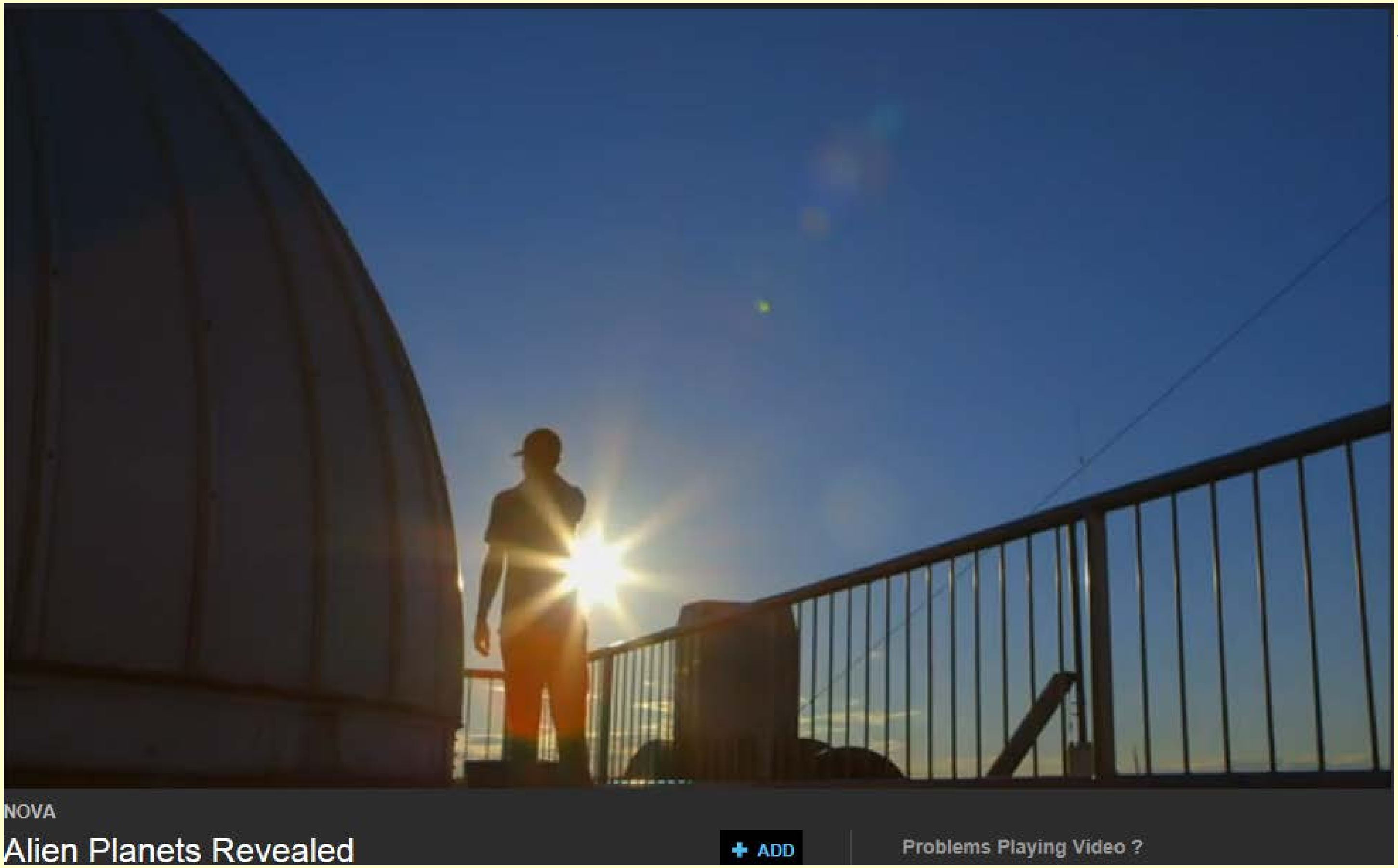
Future Projections:

- Adoption of new innovations to reduce glare, achieve gradual diffusion & omni-directionality
- Manufacturing Opportunities: design optimization (thermal, optical, mechanical, electrical: interrelated!)
- Opportunities for materials/fabrication & manufacturing
  → reduce cost and increase reliability

LED Glare must be resolved

Create a continuously curved LED lamp at the micro level

Don't take my word for it! → Nature shows the answer (divergence theorem) everyday!




NOVA
Alien Planets Revealed
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Thank you!