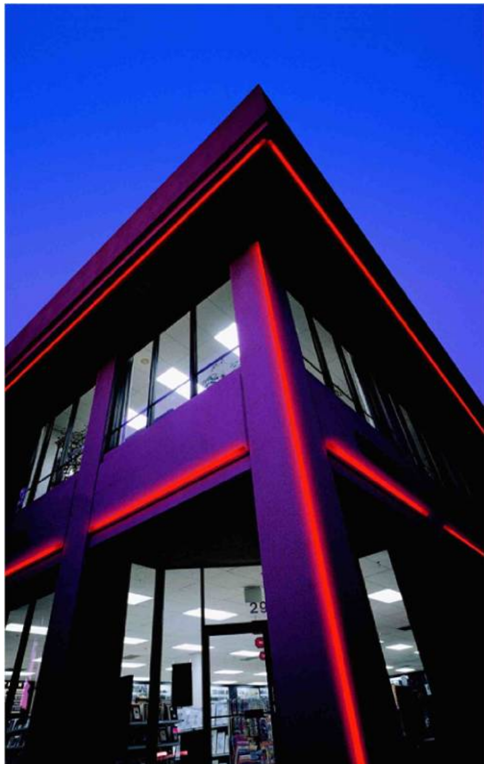
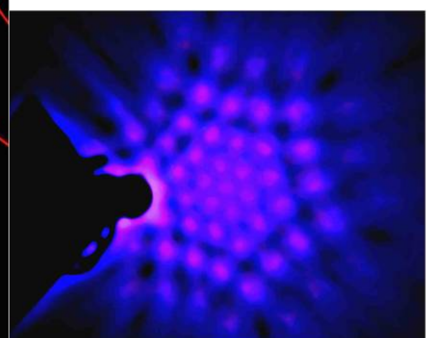
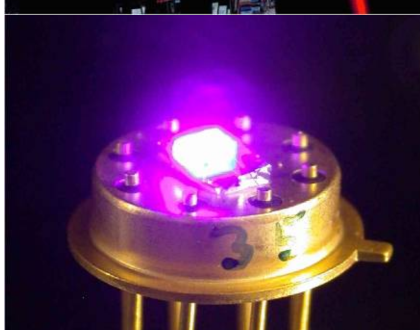


Basic Research Needs for Solid State Lighting: LED Science

Jerry A. Simmons
Sandia National Laboratories

Sandia National Laboratories

Acknowledgements

Basic Research Needs for SSL LED Science Panel

Bob Davis (Carnegie Mellon U)
Jerry Simmons (SNL)
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Mary Crawford (SNL)
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Eugene Haller (LBNL)
Andreas Hangleiter (TU Braunschweig)
Mike Krames (LumiLeds)
David Norton (U of Florida)
Jasprit Singh (U of Michigan)
Jim Speck (UCSB)
Stephen Streiffer (Argonne)
Christian Wetzel (RPI)

Special thanks to…

Jeff Tsao (SNL)
Mary Crawford (SNL)
Mike Coltrin (SNL)

Outline

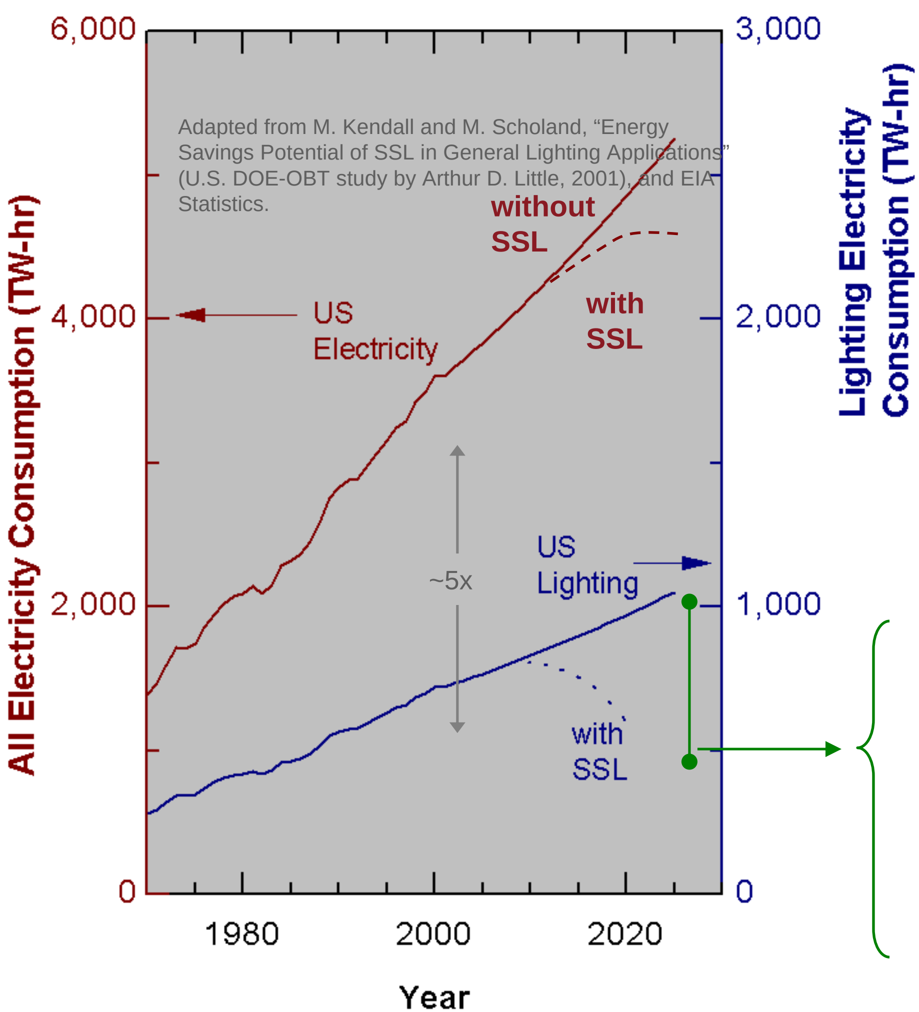
- Metrics for LED performance
- Approach of the BRN-SSL LED Science Panel
- LED-relevant ***Priority Research Directions*** (PRDs)

LED PRDs

Cross-Cutting RDs

http://www.science.doe.gov/bes/reports/list.html

Effect of market adoption of 50% efficient SSL



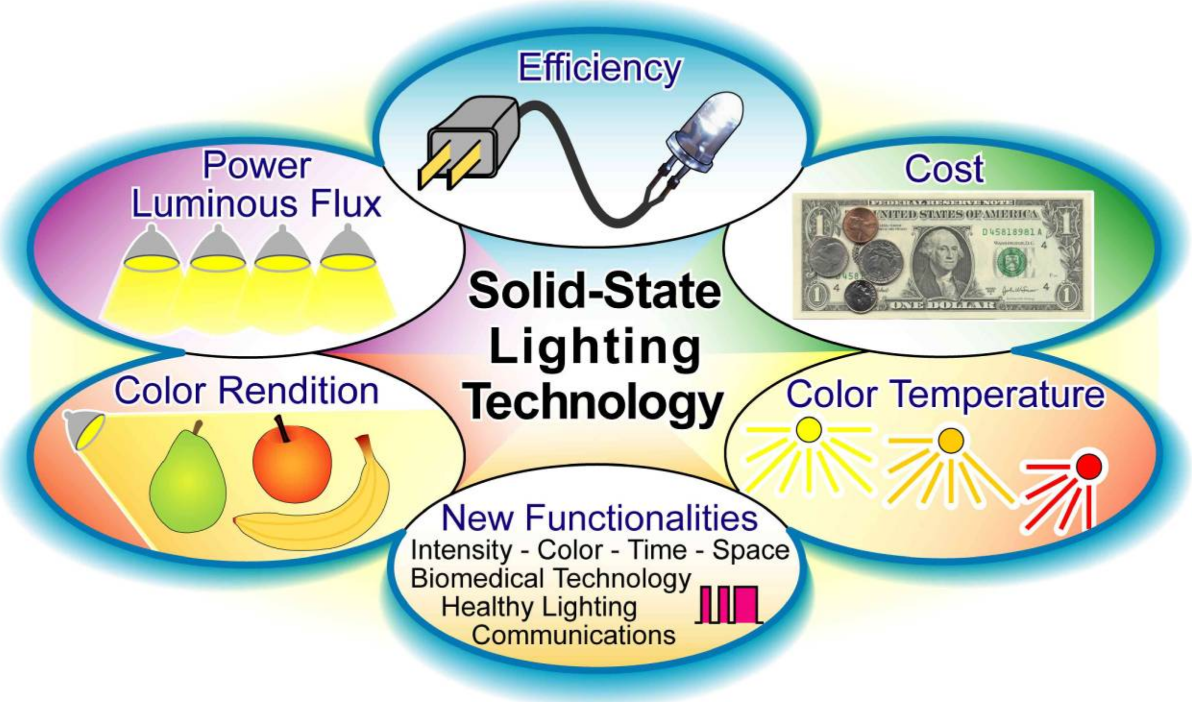
- SSL has the potential, by 2025, to:
  - decrease electricity consumed by lighting by 62%
  - decrease total electricity consumption by 13%

Projected Year 2025 Savings (complete replacement)	US	World
Electricity used (TW-hr)	620/ year	1,800/ year
$ spent on Electricity	42B/ year	120B/ year
Electricity generating capacity (GW)	70	~200
Carbon emissions (Mtons)	100	~300

Other metrics for SSL performance

Other performance metrics:

- Lamp power
- Cost
- Lifetime
- Directionality
- Operating temp
- Correlated Color Temp (CCST)
- Color Rendering Index (CRI)



Courtesy E.F. Schubert, RPI

Color Rendering Index (CRI) is a critical factor

"The color rendering index (CRI), is a measure of the ability of a light source to reproduce the colors of various objects being lit by the source (100 is the best CRI)."

Light source	*CRI*
Sunlight	100
W filament incandescent light	100
Fluorescent light	60 – 85
Existing Phosphor-based white LEDs/OLEDs	60 – 90
Na vapor light	40

Courtesy F. Schubert (RPI) and G. Jabbour (ASU)

Lifetime

"Old LEDs never die; they simply fade away."

With apologies to General Douglas C. MacArthur

Lifetimes of many commercially available LEDs are rated at 50,000 hours. "Lifetime" is defined as time to 70% of original lumen output.

SSL-LED Technology Roadmap Targets

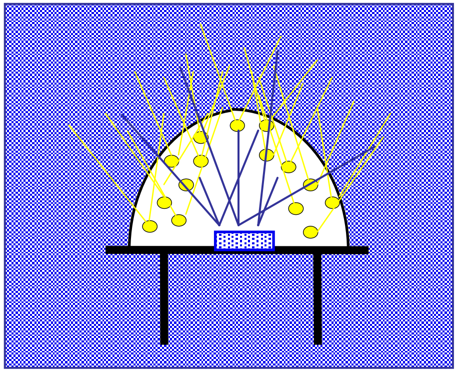
TECHNOLOGY	SSL-LED 2002	SSL-LED 2007	SSL-LED 2012	SSL-LED 2020	Incande-scent	Fluore-scent
Luminous Efficacy (lm/W)	25	75	150	200	16	85
Lifetime (hr)	20,000	>20,000	>100,000	>100,000	1,000	10,000
Flux (lm/lamp)	25	200	1,000	1,500	1,200	3,400
Input Power (W/lamp)	1	2.7	6.7	7.5	75	40
Lumens Cost ($/klm)	200	20	<5	<2	0.4	1.5
Lamp Cost ($/lamp)	5	<5	<5	<3	0.5	5
Color Rendering Index (CRI)	75	80	>80	>80	95	75

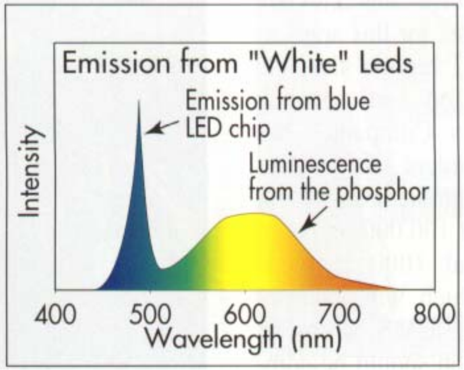
Taken from the 2002 DOE/OIDA LED Technology Roadmap

The SSL community is just about on target in 2007.

How to make a white LED

- UV/Blue InGaN LED-pumped phospors





Commercial approach to date (Up to 150 lm/W achieved*) …relatively low cost
*** Nichia**

CRI of blue LED + yellow phosphor is ~70

- Multi-chip/ multi-color LEDs (RGB)

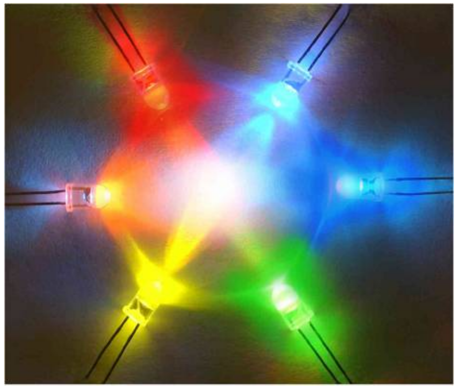
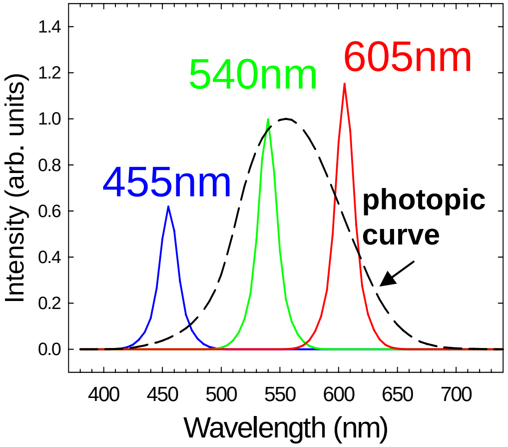


Figure courtesy of E. F. Schubert



Potentially most efficient, highest quality white lighting approach *…but high cost*

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Current State of the Art

Commercial White LEDs are breaking the 100 lm/W barrier

Nichia: Small area White LED*

Current	20 mA
Lumens	9.4
Lumens per Watt	150
CCT (K)	4600

* 12/20/2006 press release

Cree Lighting: Small area White LED*

Current	20 mA
Lumens per Watt	131
CCT (K)	6027

* 06/20/2006 press release

Philips Lumileds: High-Power, 1 x 1 mm chip White LED*

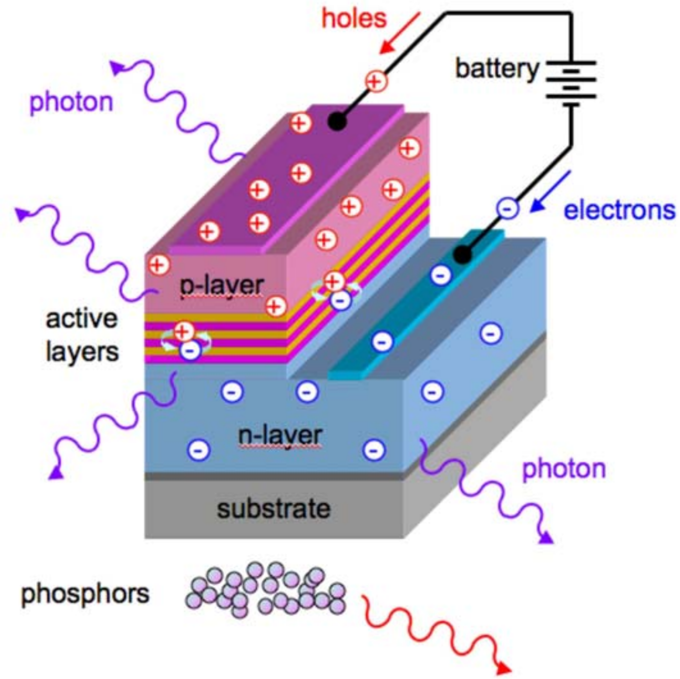
Current	350 mA	2000 mA
Lumens	136	502
Lumens per Watt	115	61
Watts	1.2	8.3
CCT (K)	4685	

* 01/23/07 press release

Approach of the LED Science Panel

Consider the life-cycle of a "white LED Photon":

- What stages in the life-cycle are poorly understood and/or poorly controlled?
- Where might increased understanding lead to improved SSL technology?



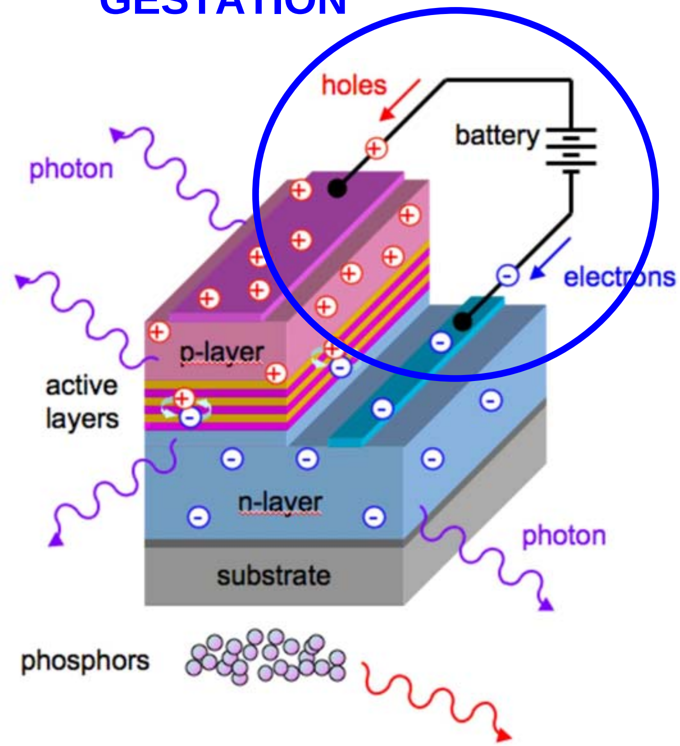
A major focus is the InGaN materials system.

Approach of the LED Science Panel

Consider the life-cycle of a "white LED Photon":

- What stages in the life-cycle are poorly understood and/or poorly controlled?
- Where might increased understanding lead to improved SSL technology?

GESTATION



(1) Injection and transport of charge carriers
(injection efficiency E_{inj})

Approach of the LED Science Panel

Consider the life-cycle of a "white LED Photon":

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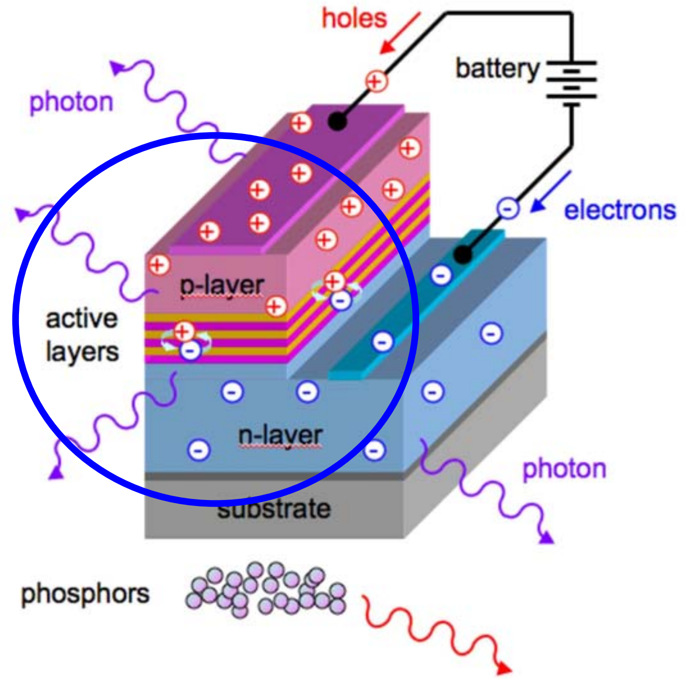
- Where might increased understanding lead to improved SSL technology?

BIRTH



(1) Injection and transport of charge carriers
(injection efficiency E_{inj})

(2) Radiative and non-radiative recombination
(internal quantum efficiency η_{int})

Approach of the LED Science Panel

Consider the life-cycle of a "white LED Photon":

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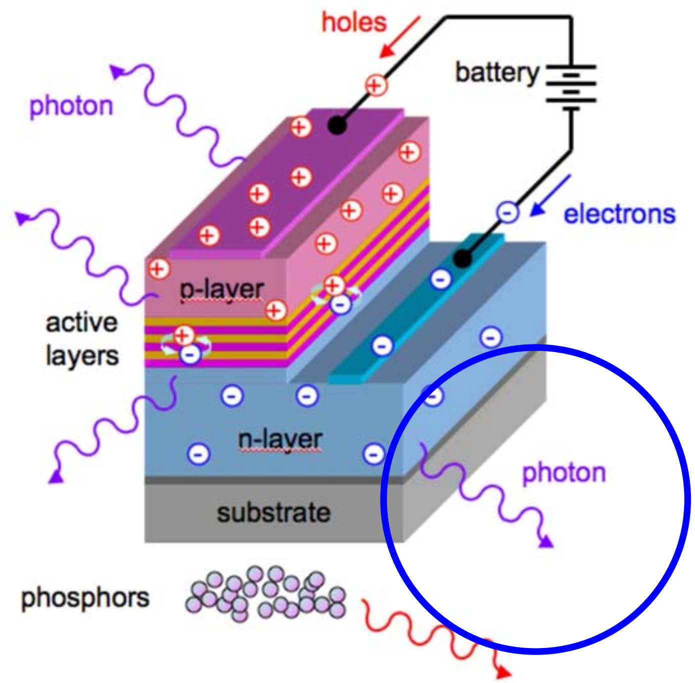

(1) Injection and transport of charge carriers
(injection efficiency E_{inj})

(2) Radiative and non-radiative recombination
(internal quantum efficiency η_{int})

(3) Light extraction from the die
(light extraction efficiency C_{ext})

EDUCATION & TRAINING

Approach of the LED Science Panel

Consider the life-cycle of a "white LED Photon":

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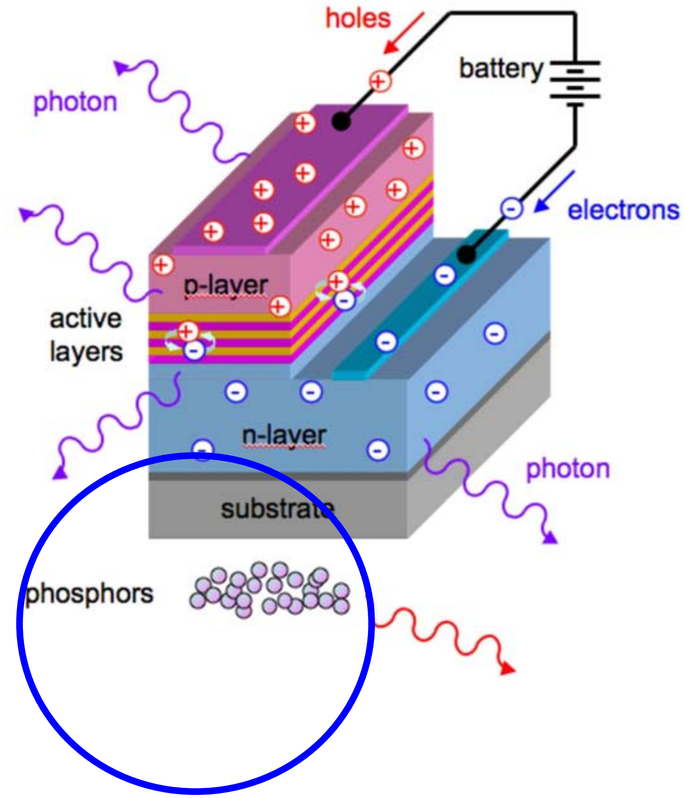
- Where might increased understanding lead to improved SSL technology?



(1) Injection and transport of charge carriers
(injection efficiency E_{inj})

(2) Radiative and non-radiative recombination
(internal quantum efficiency η_{int})

(3) Light extraction from the die
(light extraction efficiency C_{ext})

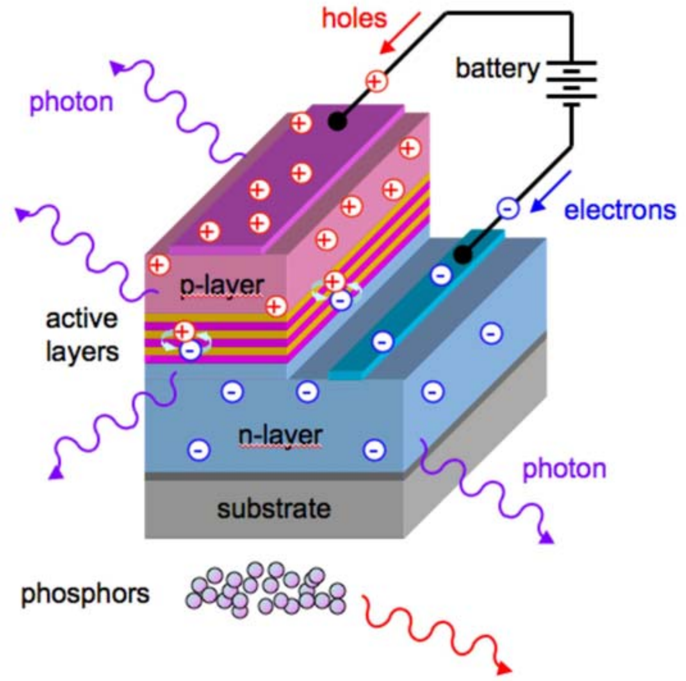
(4) Color conversion and multi-color mixing
(optical element & Stokes shift losses)

MOVE OUT OF HOUSE AT MATURITY

Gestation: Charge injection and transport

Challenges for wide bandgaps (GaN)

- Acceptor energy levels are very deep (0.2 - 0.3 ev)
- Tendency for dopant compensation
- Low p carrier concentrations:
  - p = mid 10^{18} cm-3
  - n = mid 10^{19} cm-3
- Low p mobilities:
  - p = ~10 cm^2/Vs
  - n = ~1000 cm^2/Vs
- p-type contacts have high resistance
  - p: 10^{-2} - 10^{-5} Ω-cm^2
  - n: 10^{-5} - 10^{-8} Ω-cm^2



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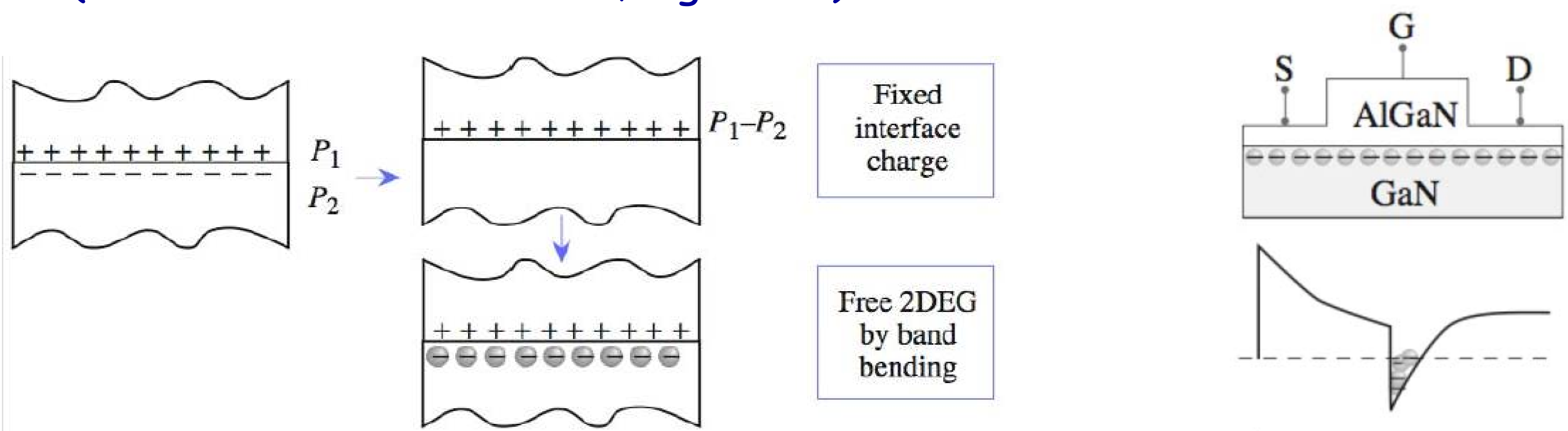
PRD: Polar Materials and Heterostructures

- Because bandgaps tend to increase with bond polarity, most known inorganic wide bandgap semiconductors (including InGaN) are polar. This property is dramatically different from most other III-V materials.
- This Priority Research Direction (PRD) proposes a concerted effort aimed at ***manipulating and understanding the electronic and optoelectronic properties of polar materials and heterostructures.*** (Includes GaN and others, e.g. ZnO.)

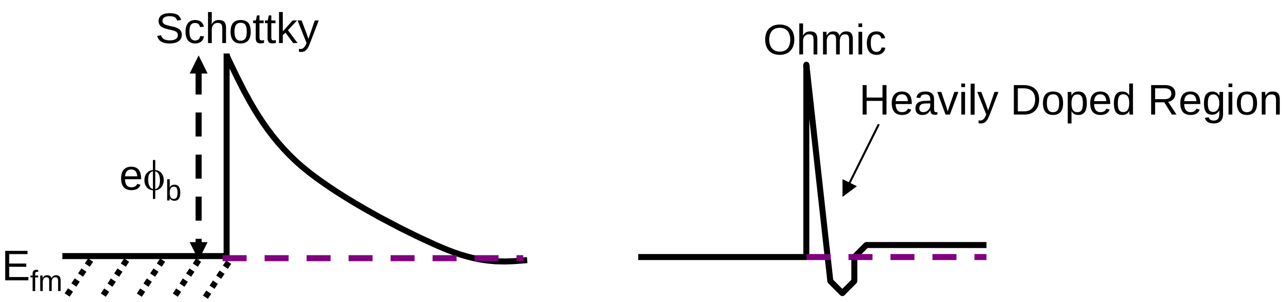


Can we achieve highly conductive p-layers using polarization effects?

PRD: Polar Materials and Heterostructures

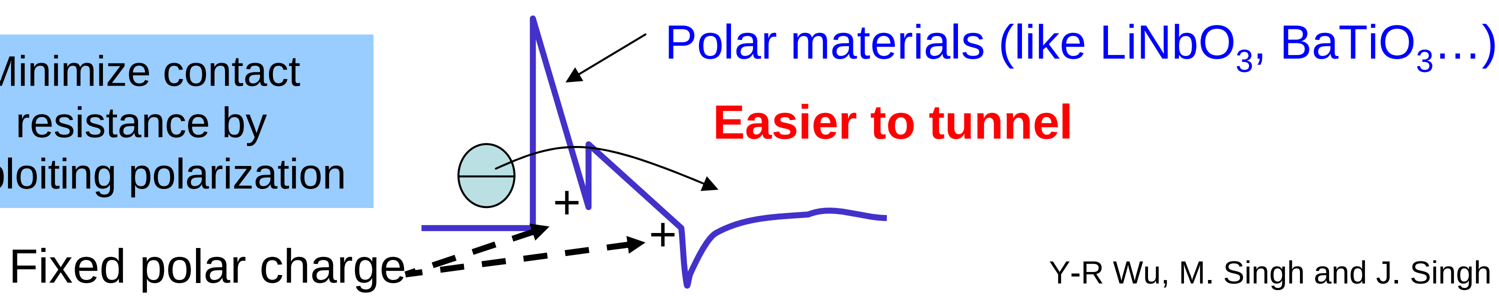
Science questions and opportunities

- Can polarization be used for doping and lower resistance p-type contacts and to enhance majority transport?
- Can charge be channeled into the active region under high injection conditions?



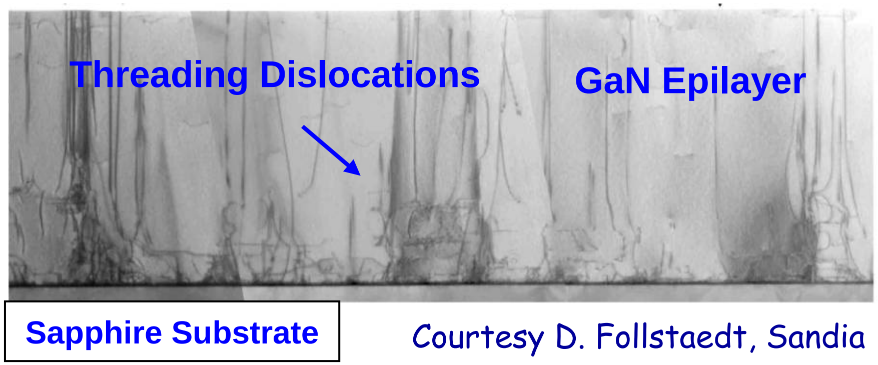
Challenges in heavy p-doping for large bandgaps

Minimize contact resistance by exploiting polarization



Y-R Wu, M. Singh and J. Singh
JAP V94 p5826, 2003.

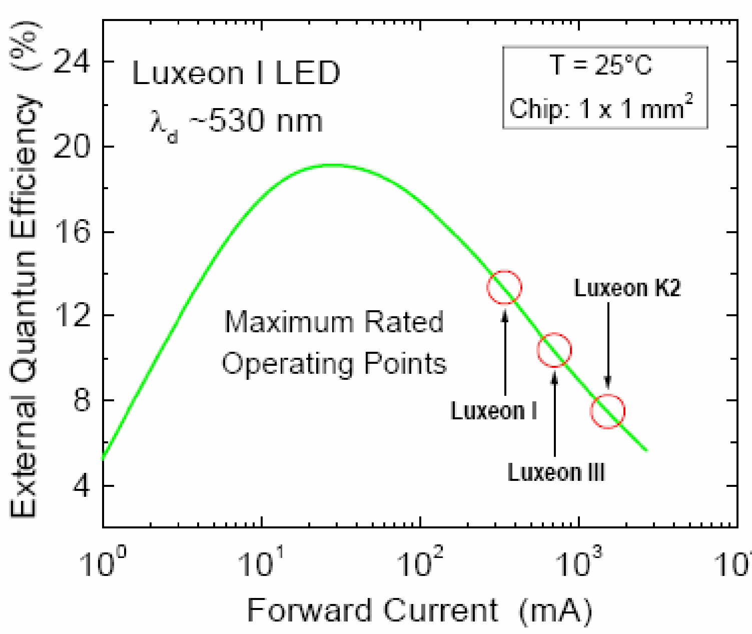
Birth: Radiative & non-radiative recombination



Courtesy D. Follstaedt, Sandia

Challenges:

- InGaN LED operation in presence of high defect densities (~10^9 cm^{-2}) little understood. *(Why do they work at all?)*
- Rollover of efficiency with high current densities little understood and of great importance

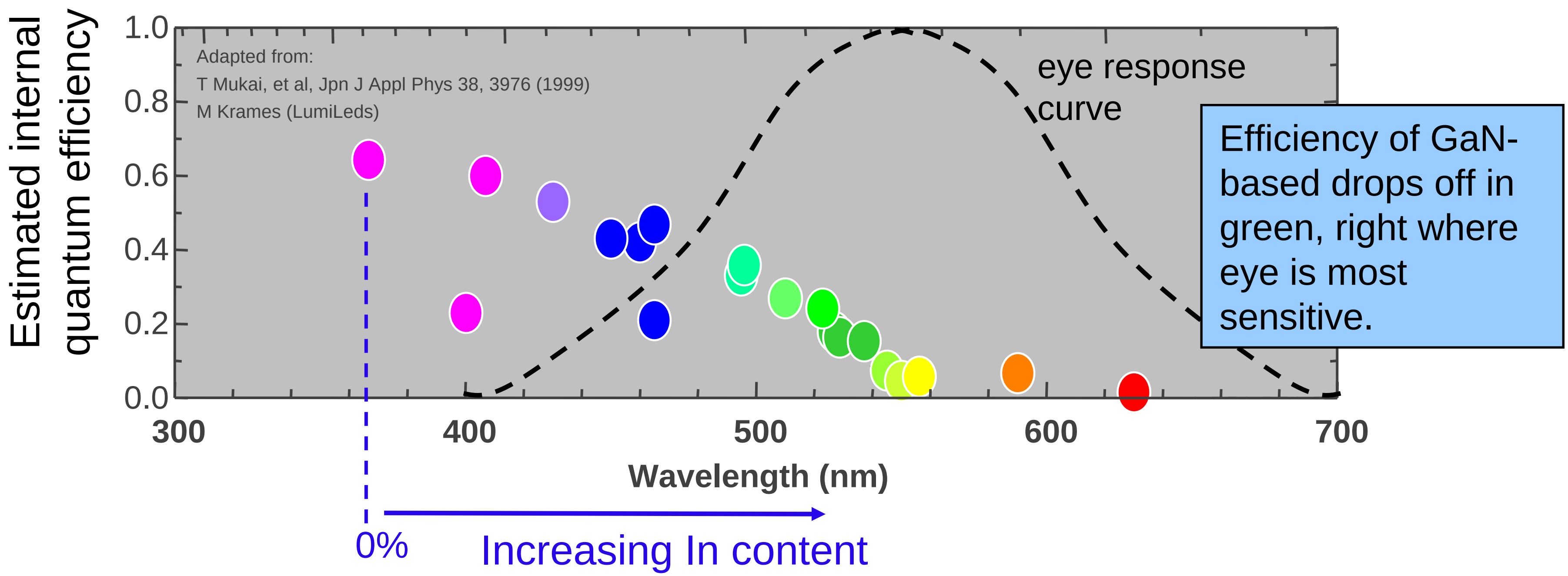


Courtesy G. Craford, Lumileds

Birth: Radiative & non-radiative recombination

Another Challenge:

- Internal quantum efficiencies of high-In (green and yellow) LEDs are poor



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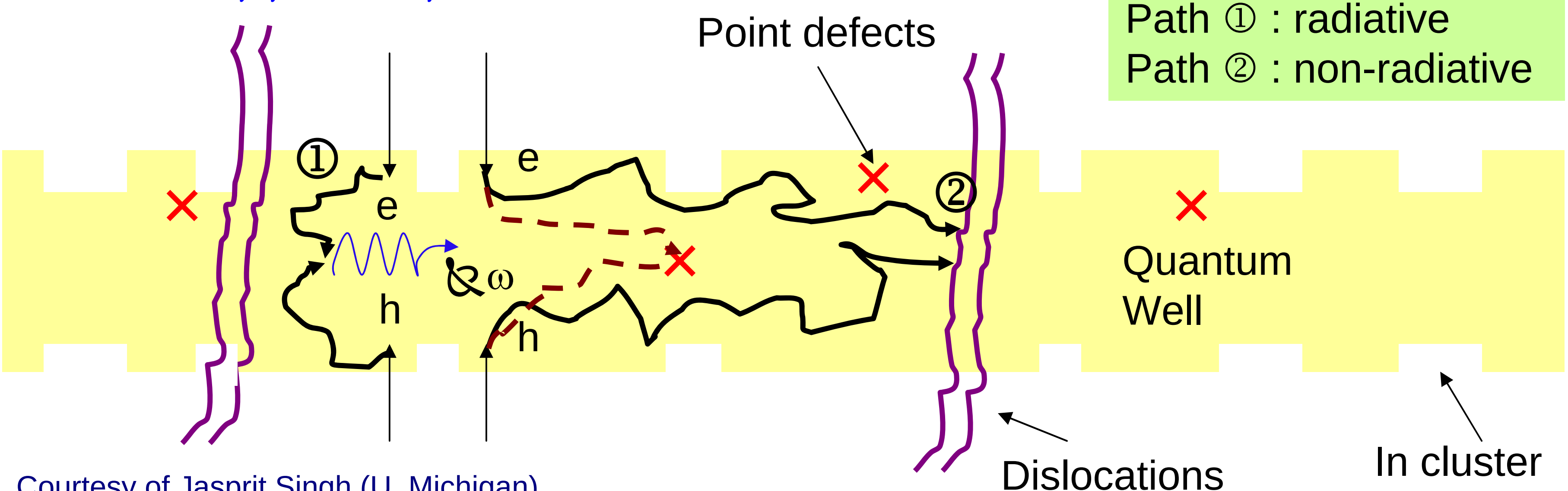
PRD: Luminescence efficiency in InGaN

Need to understand how radiative recombination is affected by the complex interplay of:

- *charge carrier transport*
- *quantum confinement*
- *polarization and strain-induced fields*
- *point & extended defects*
- *In alloy phase separation*



Courtesy of Jasprit Singh (U. Michigan)

PRD: Luminescence efficiency in InGaN

Science Questions:

(1) Could the "V-defects" that decorate dislocations be producing energy maxima that repel carriers?

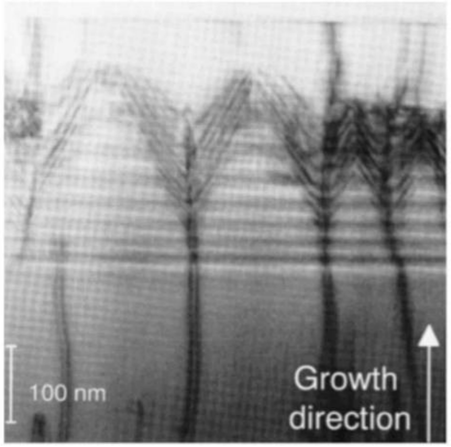
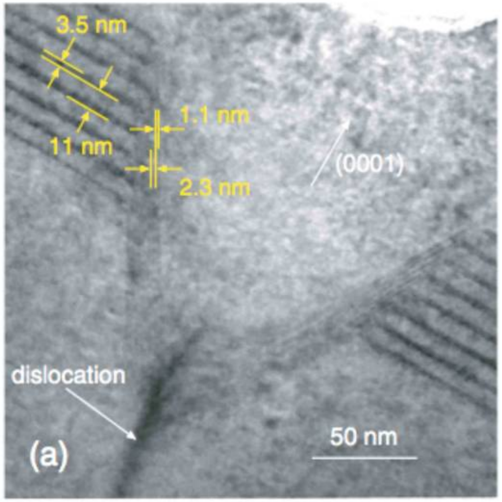
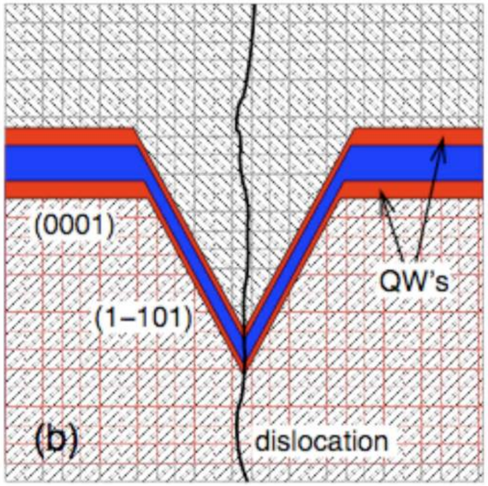
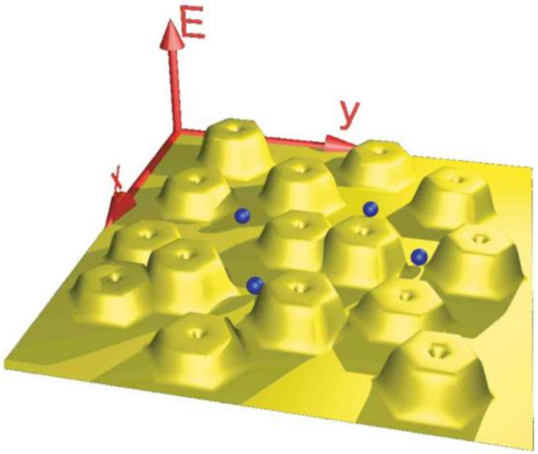


Figure from Scholz et al., Mat Sci Eng B 50, 238 (1997)





A. Hangleiter et al.,
Phys. Rev. Lett. 95, 127402 (2005)



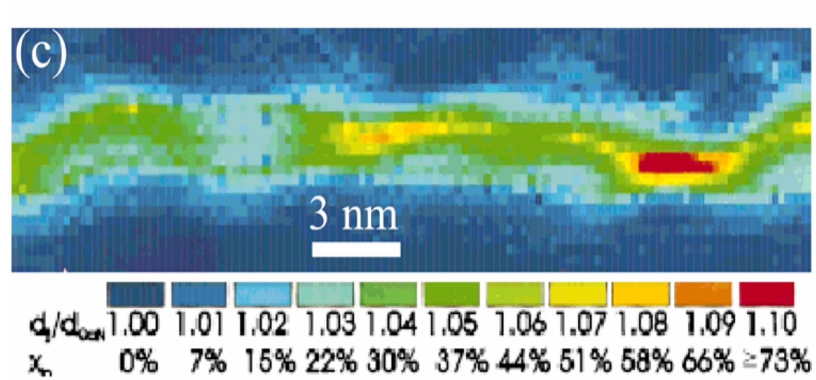
PRD: Luminescence efficiency in InGaN

Science Questions:

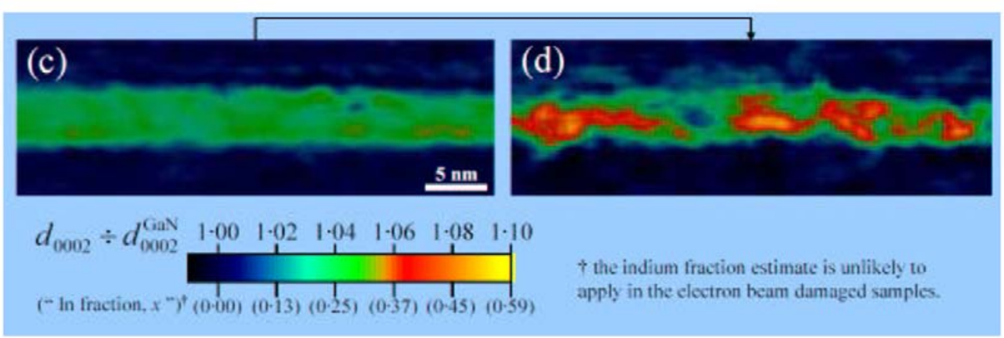
(2) How does increasing In content affect luminescence? Could In compositional clustering localize carriers away from dislocations and point defects?

This is critical to understanding the green-yellow performance gap!

Reports of In composition variations



Gerthsen *et al.*, Phys. Stat. Sol. A **177,** 145 (2000) .



Smeeton et al., APL 83, 5419 (2003).

But recent reports demonstrate In and strain variations caused by TEM materials damage. ***Are In composition variations in InGaN QWs real?***

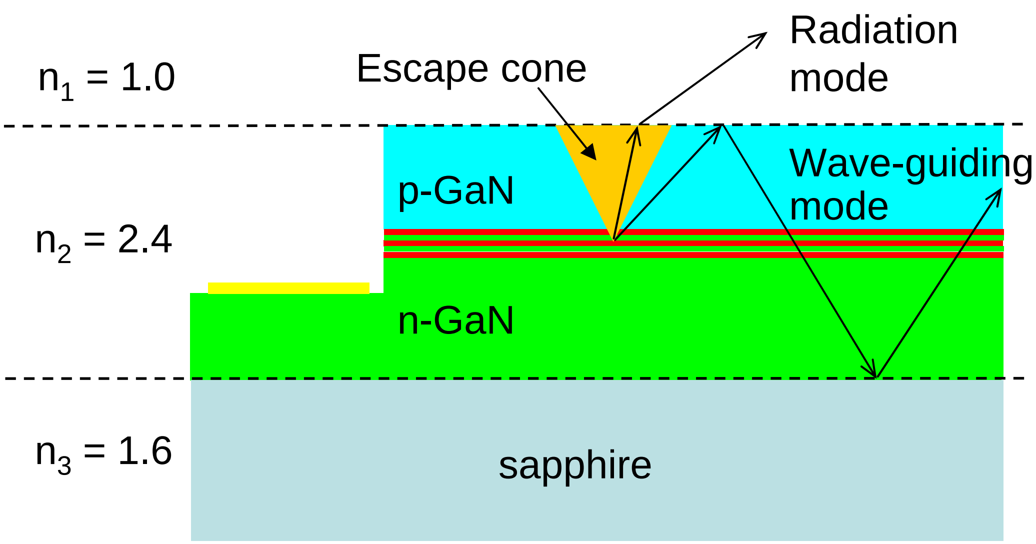
Ed & Training: Device physics and light extraction

Challenges:

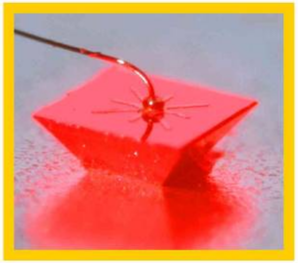
- Photons are trapped inside high index layer (total internal refection). Reflect until absorbed.
- LED light extraction efficiencies remain surprising low: typical state-of-art is at 50-60%

For unencapsulated LEDs:

- Escape cone = 25 deg
- Escape cone solid angle = 4.5% of total (per surface)

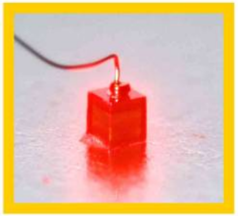


Ed & Training: Device physics and light extraction

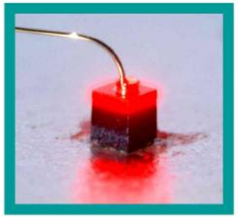


TIP-LED
Chip
2000

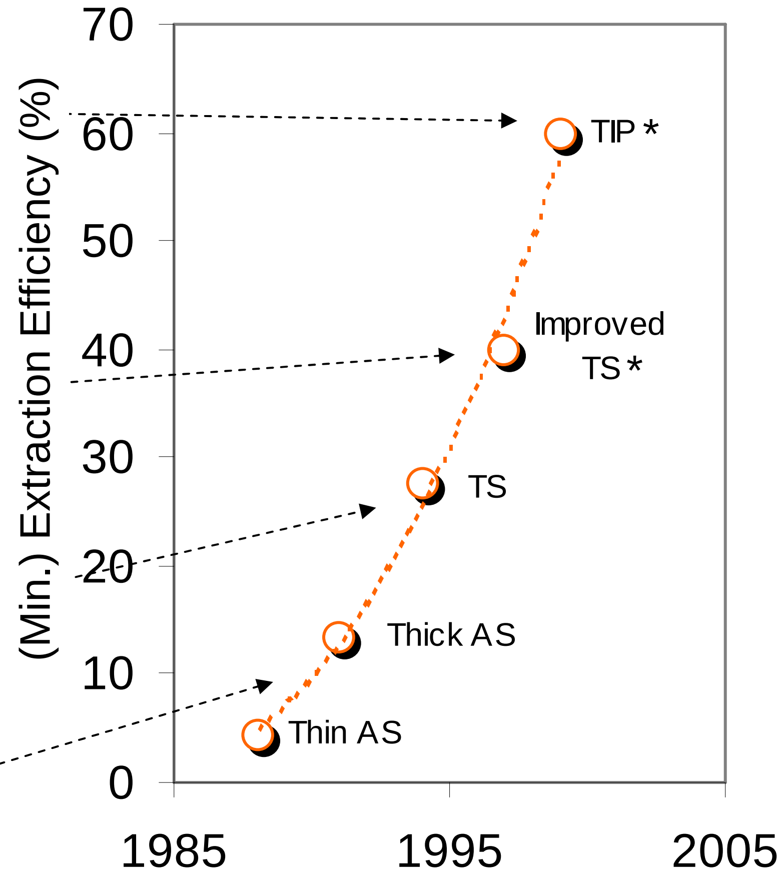
High-Power
TS Chip
1998



Transparent
Substrate
1994



Absorbing
Substrate
1991



*Based on max. measured external quantum efficiency.

Courtesy of M. Krames, Lumileds

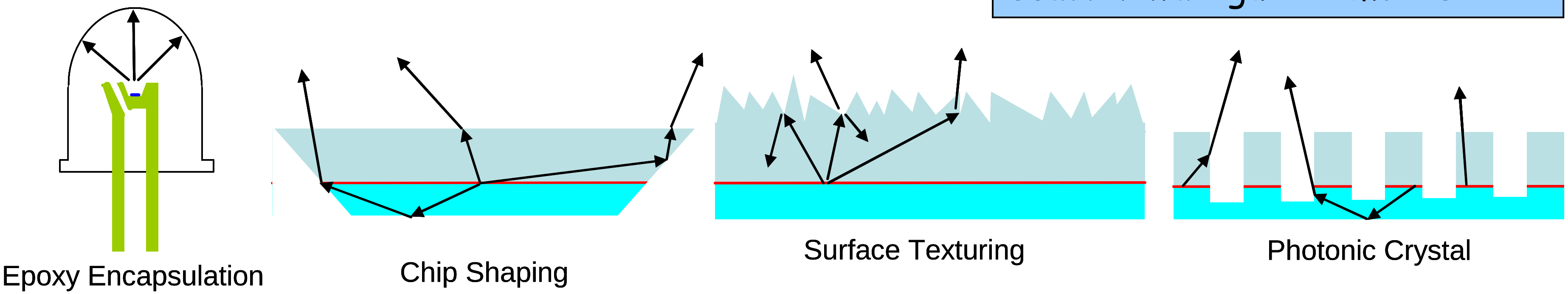
CCRD: Innovative Photon Management

A PREVIEW: Photonic Crystal LEDs

Science Questions:

(1) How might nanoscale photonic structures be used to increase light extraction efficiency through geometric effects?

Use photonic crystal to Bragg-scatter waveguided modes



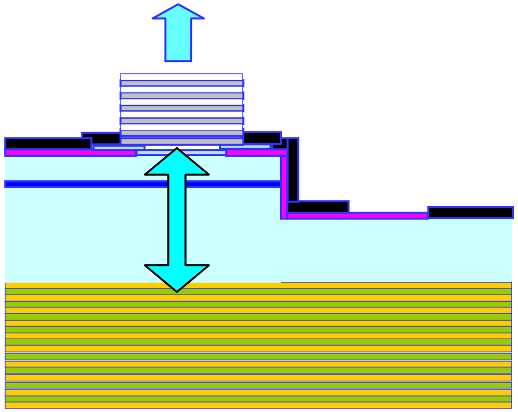
CCRD: Innovative Photon Management

Science Questions:

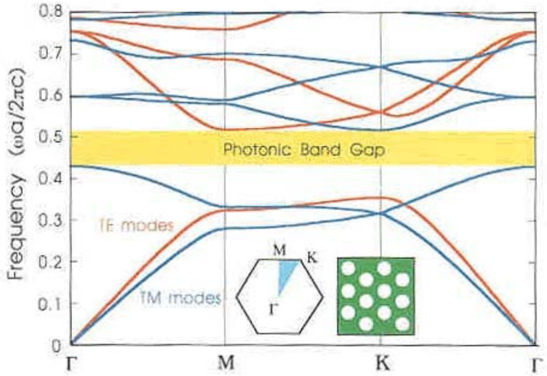
(2) Can the photon modes and photonic density of states be manipulated to control the direction of emission?
(Avoid waveguiding modes in the first place.)

(3) Can the internal quantum efficiency be modified?

Resonant Cavity LEDs



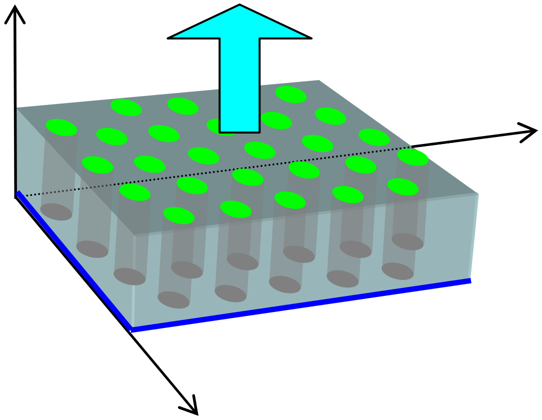
Courtesy of Arto Nurmikko (Brown U)



r/a=0.48 and ε =13

J. D. Joannopolous, et. al "Photonic Crystals"

Photonic Crystal LEDs



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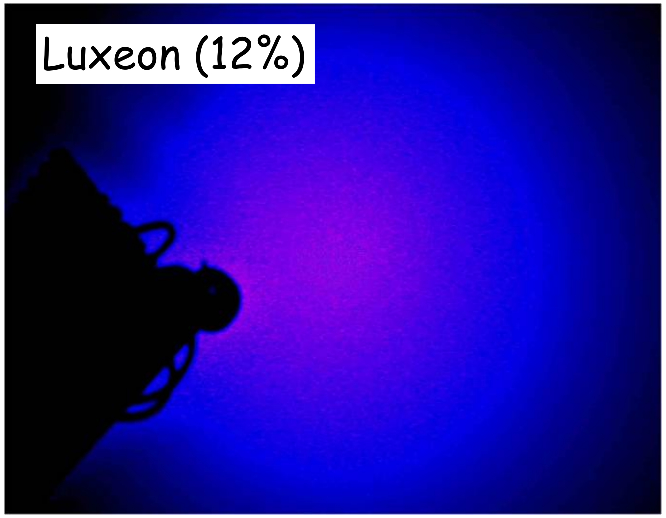
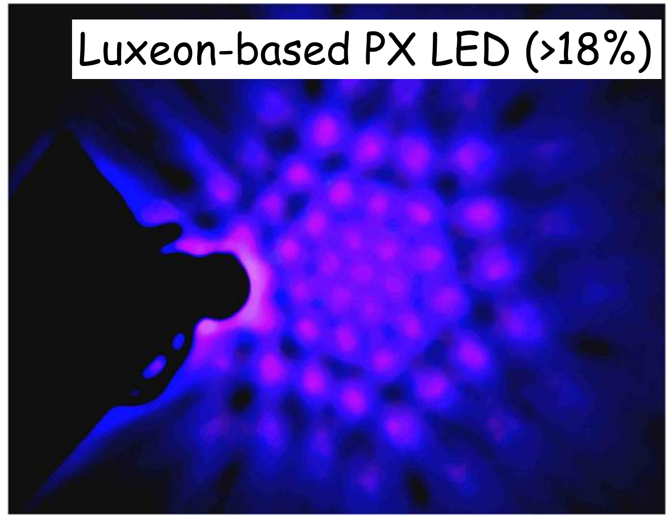
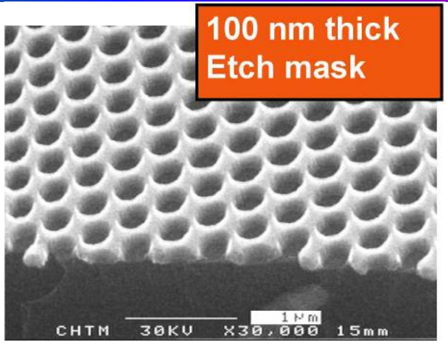
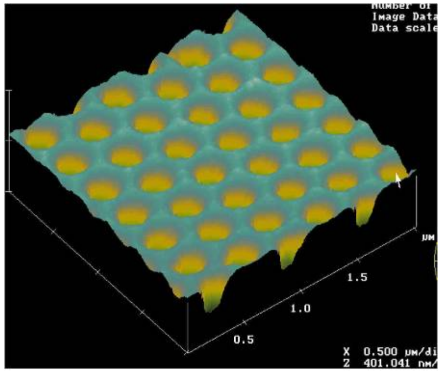
CCRD: Innovative Photon Management



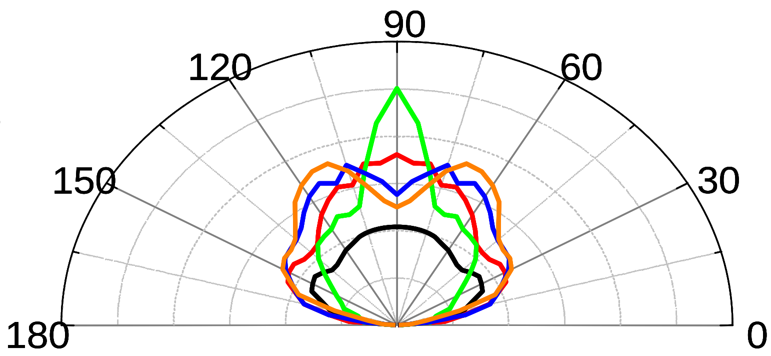






Lumileds, Sandia, and UNM (Wierer et. Al., APL 84, 3885 (2004)

- First ever large area ($1mm^2$) III-Nitride photonic crystal LED. (Interferometric litho by S. Brueck.)
- Far field pattern is modified
- ***External Quantum Efficiency increased by >50%.***



Changes in spontaneous emission rates (Purcell Effect) could further increase efficiency

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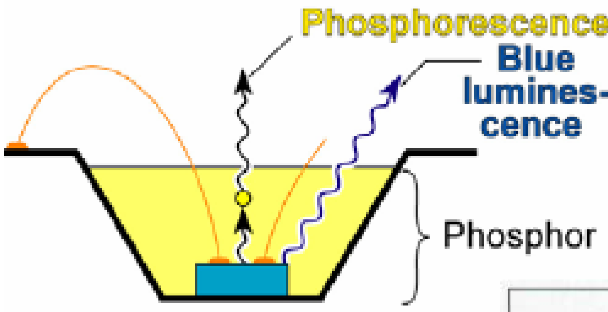
Move out at Maturity: Photon Conversion

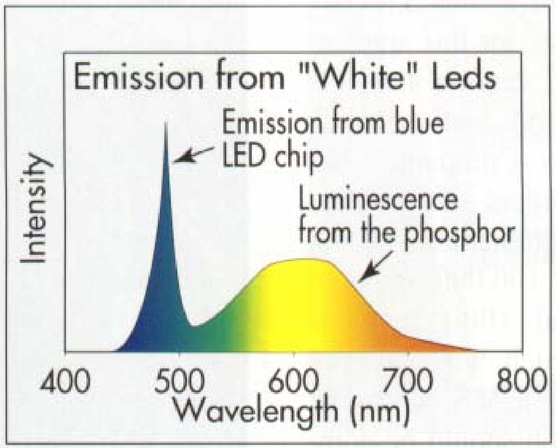
Challenges:

- Phosphors (developed over decades) for fluorescent lighting absorb near 250 nm and are *unsuitable for SSL*
- Phosphors for SSL have substantial room for efficiency improvements, *especially red.*
- Need fast photoluminescence lifetimes (no saturation), high-T operation, low cost, non-toxic, compatibility with encapsulants, and long lived under high UV flux



Blue + Yellow CRI = ~70

Need CRI ≥ 90!



Backscattering of light by large phosphor particles is a significant loss!

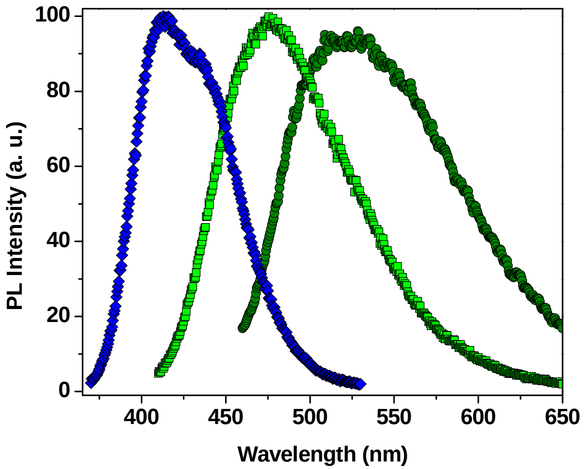
PRD: Photon Conversion Materials

Potential Research Approaches

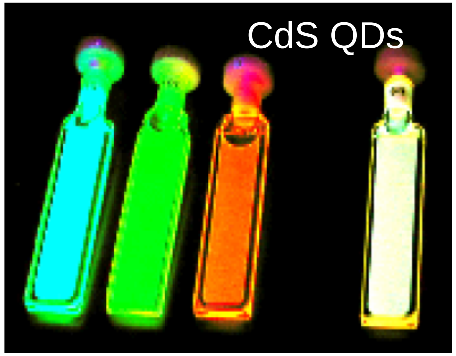
Bulk phosphor materials:
- Eu^{2+} and Ce^{3+} are the only common rare earths with 4f - 5d transitions that are parity allowed, and hence intense
- Chemical synthesis of novel oxide & nitride host structures
- *First principles design, not combinatorial methods*

New encapsulants/binder matrices
- Should survive high temps and UV/blue irradiation
- Low-temperature deposited *inorganic* encapsulants (e.g. silica)

Nanocrystalline QDs
- Tunable through size and surface ligand coverage
- Reduced light back-scattering
- Issues of long-term stability, high-T operation
- *Need non-toxic materials!*



Control of excitation and emission energies by manipulation of host structure and chemistry $Sr_{2-x}Ba_xSiO/N_4;Ce^{3+}$ (Le Toquin and Cheetam, pending)



Single Color Multicolor/White

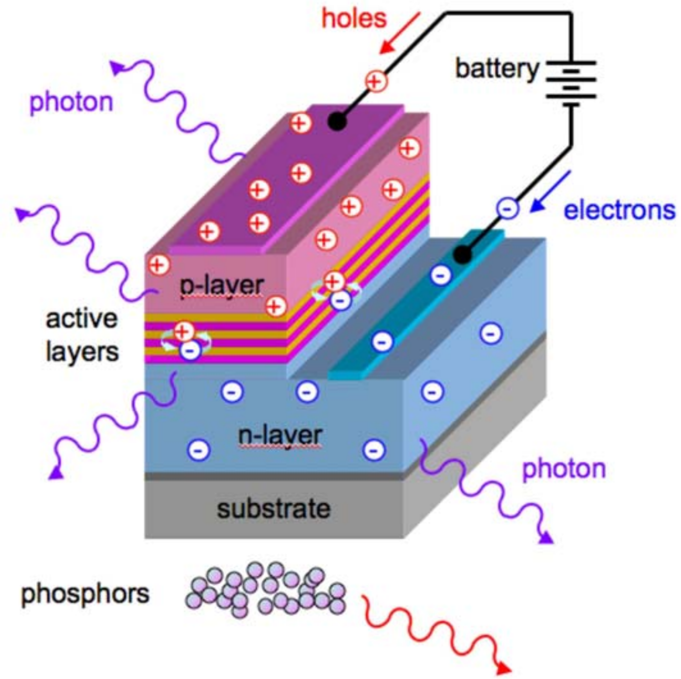
Materials Synthesis

Challenges:

Bright GaN LEDs are fairly new (early 1990's). It is surprising that it has progressed so rapidly.

Could other better materials be out there? But can we atomically engineer a new material that could be even better?

- Non-polar?
- Self-assembled nanoscale components?
- Engineered high conductivity layers?
- Built-in QWs?

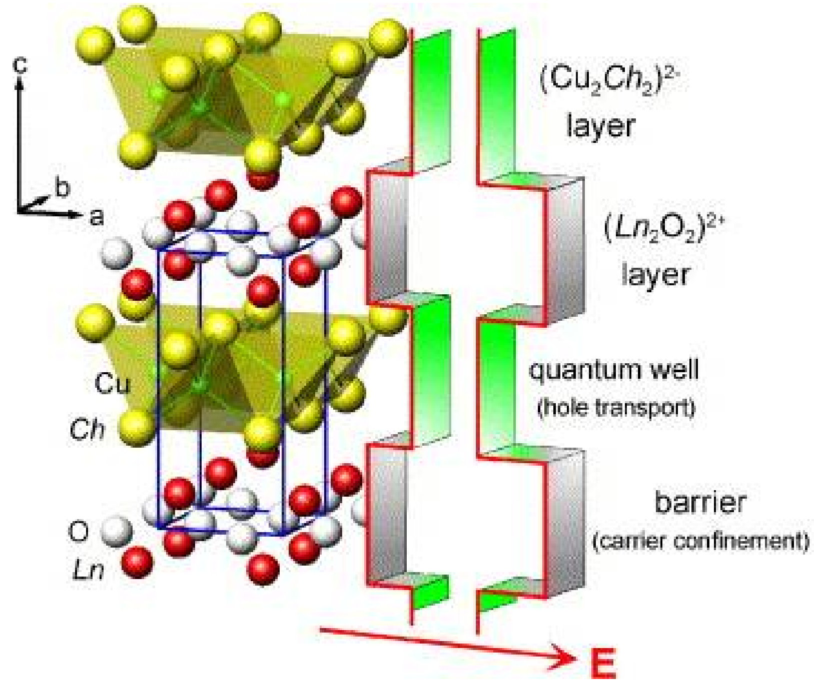


PRD: Unconventional Light-emitting Semiconductors

Example: layered 2D oxychalcogenide crystal structures - self assembled inorganic nanostructured material

Approaches:

- Designing semiconductors with specific transport and optical properties
  - –Use computational design rather than combinatorial methods
- Self-assembly of inorganic nanostructured materials



K. Ueda et al., *Thin Solid Films* **496**, 8, (2006)

Sandia National Laboratories

Where we've been: PRDs, CCRDs, and GCs

Rational design of SSL lighting structures

Controlling losses in the light emission process

Was: "Understanding radiative and non-radiative recombination pathways"

LED PRDs:

- **Polar materials and heterojunctions**
- **Luminescence efficiency of InGaN structures**
- **Unconventional light-emitting semiconductors**
- **Photon conversion materials**

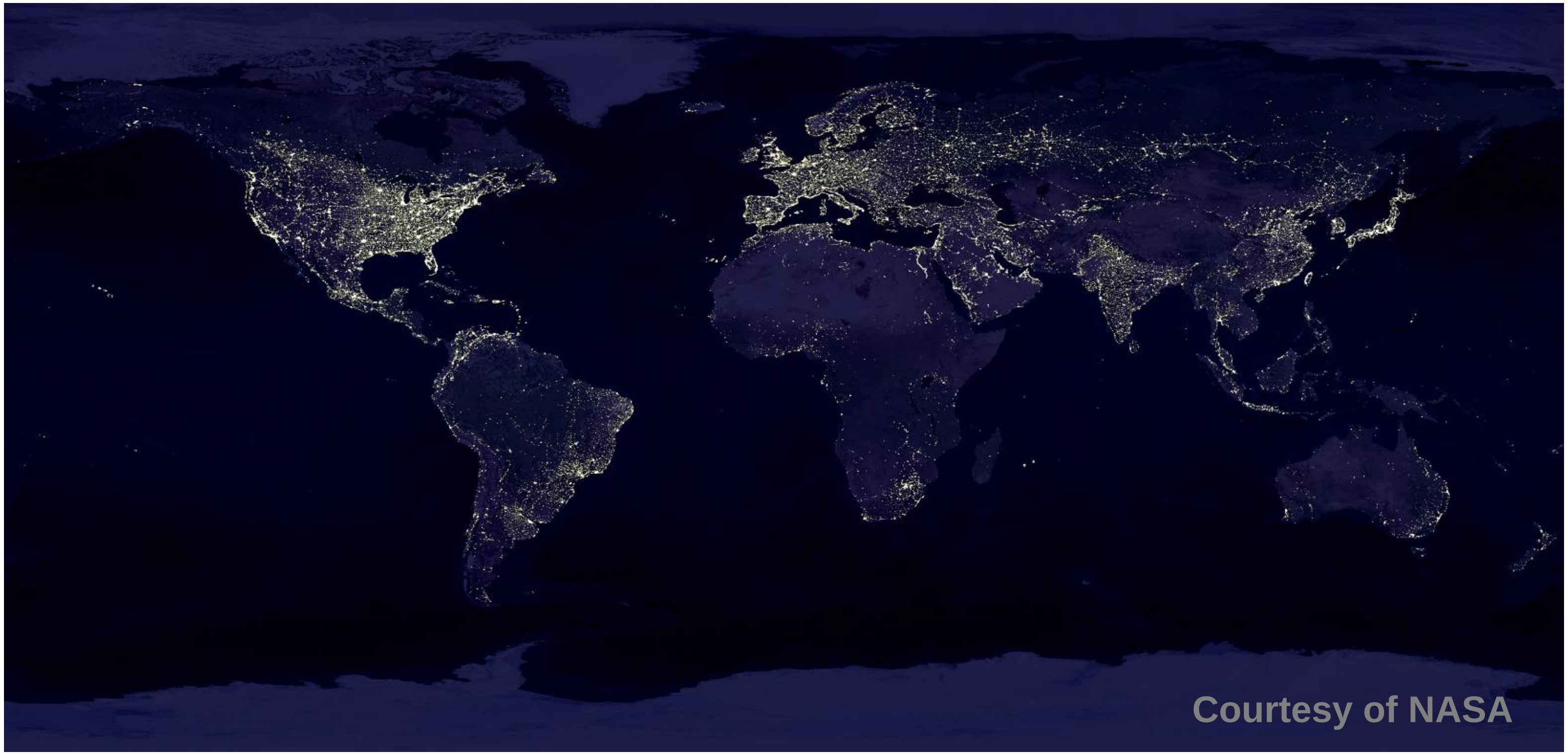
OLED PRDs:

- Managing and exploiting disorder in OLEDs
- Understanding degradation in OLEDs
- Integrated approach to OLED design

Cross-Cutting RDs:

- New functionality through heterogeneous nanostructures
- **Innovative photon management**
- Enhanced light-matter interactions
- Multiscale modeling for SSL
- Precision nanoscale characterization

Science and SSL



- 50% Energy Efficient Solid State Lighting will replace all conventional lighting in the next 25 years or so.
- This will result in a 10% reduction in global electricity use.
- Much of this revolution will be enabled by ***discovery-class science***.