Organic Technology for Solid State Lighting

and

Scientific Challenges of Solid State Lighting A DOE Basic Energy Sciences Workshop

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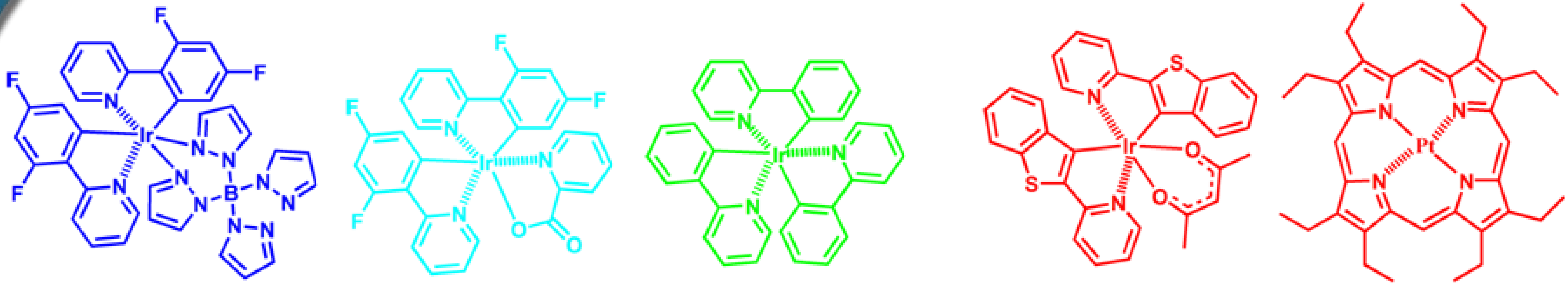
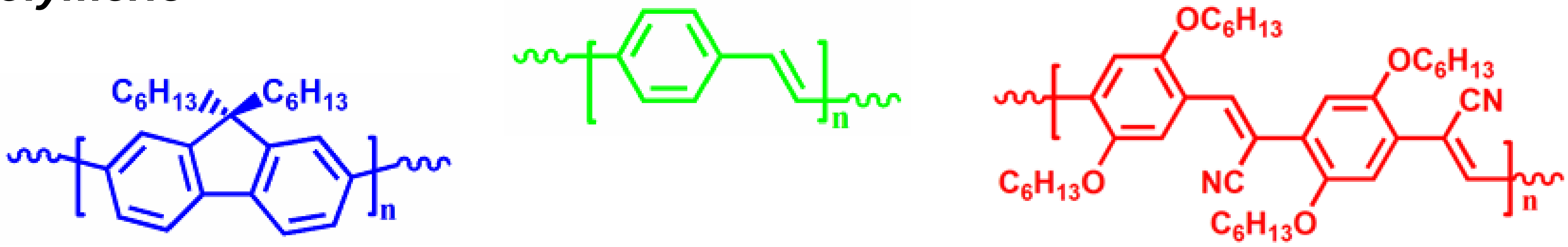
Molecular Light Emitting Materials

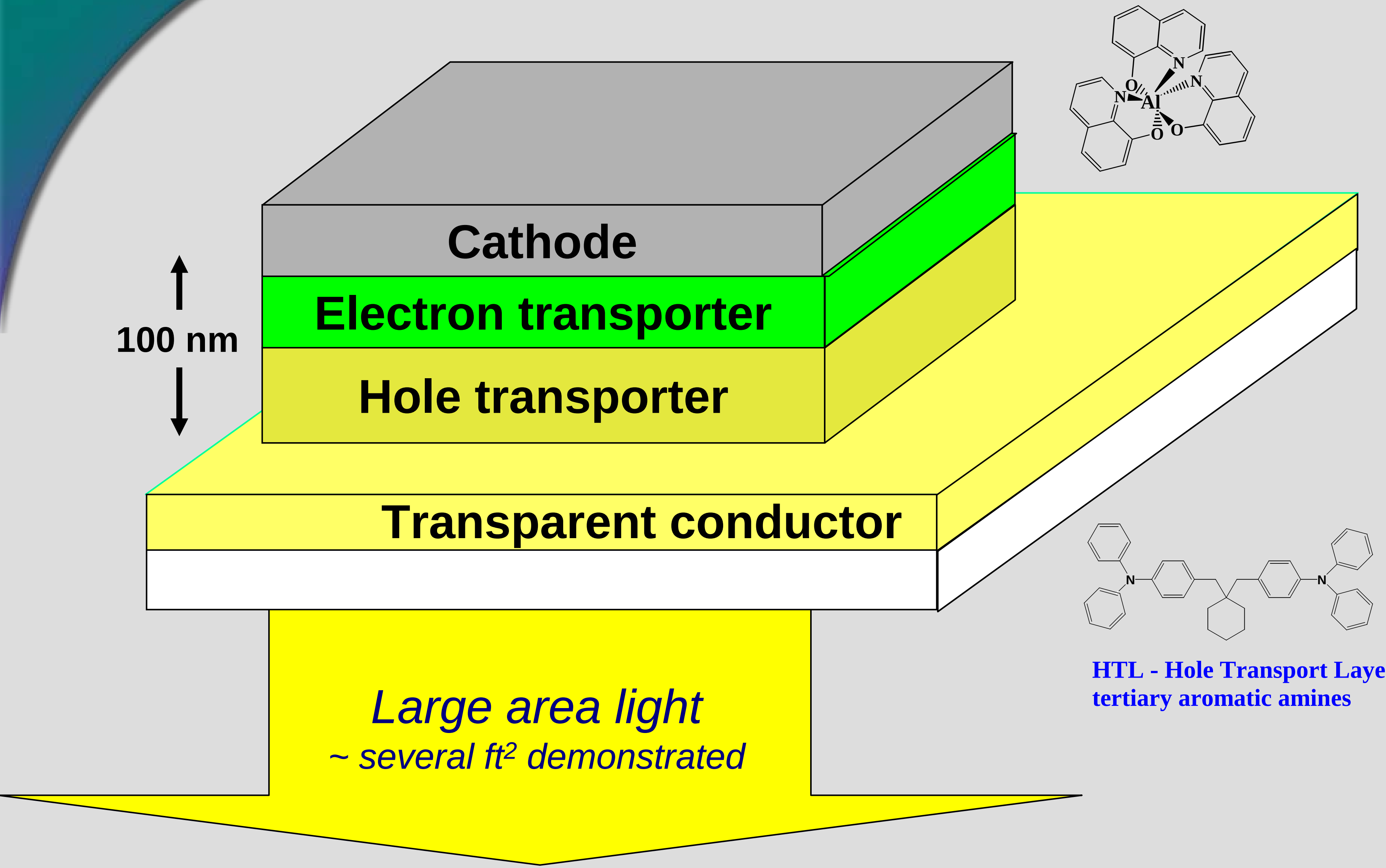


Phosphorescent

Polymeric



C.W. Tang, U.S. Patent # 4,356,429 (1980)



Cathode

Electron transporter

Hole transporter

100 nm

Transparent conductor

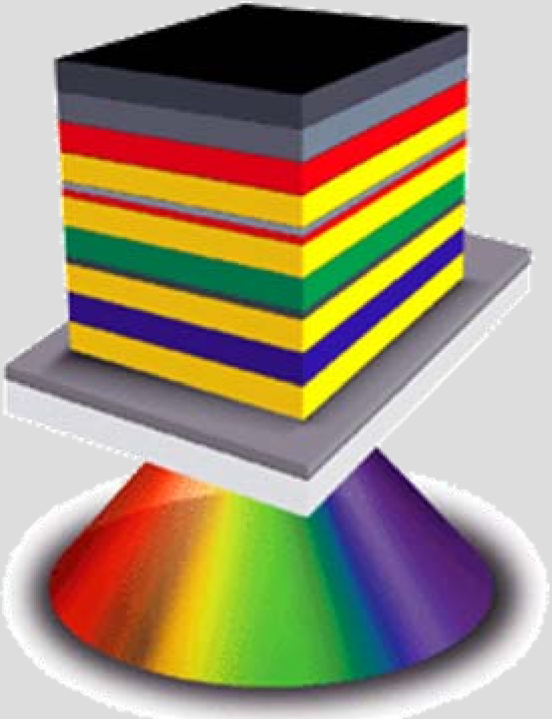
Large area light

~ several ft^2 demonstrated

HTL - Hole Transport Layer
tertiary aromatic amines

Challenges of OLEDs

- Extremely thin films lead to manufacturing challenges
- Light coupling techniques etc. must be scaled to large areas
- Extreme moisture sensitivity necessitates very low permeation encapsulation techniques



Courtesy: Universal Display Corporation

e.g. A color-tunable pixel

Z. Shen et al. Science 276, 2009 (1997)

Dupont Displays

Why OLEDs are not LEDs

	Inorganic LEDs *Crystalline, epitaxial*	**OLEDs** *Amorphous, flexible, weak adhesion, structural complexity*
p,n-doping	Generally can be either p- or n-doped with substitutional dopant atoms at $10^{15} – 10^{20}/cm^3$	Materials are *either* electron or hole conducting. Negligible background charge carrier density. Electronic doping requires 1 – 5% loading and chemically changes the host molecules
mobility	up to ~ 1000 cm^2/Vs	Holes: 10^{-3} cm^2/Vs Electrons: 0 – 10^{-4} cm^2/Vs temperature and field dependent
excited states	Electronic: light generated by weakly bound excitons, weak exciton-phonon coupling	Excitonic: correlated e^--h^+ pairs conduction bands meaningless, strongly bound excitons, strong exciton-phonon coupling, spin effects important
Purity	Well known and easily characterized using, e.g. mass spec. typically 99.9999%	Poorly characterized, uncertain role of fragments, metal ions, etc. Typical commercial purity ~ 95%

You can buy small OLED displays

MP-3 players

- eMagin (Bellevue, WA)
  - Full SVGA stereovision (800 x 3 x 600), 16.7 Million color OLED headset

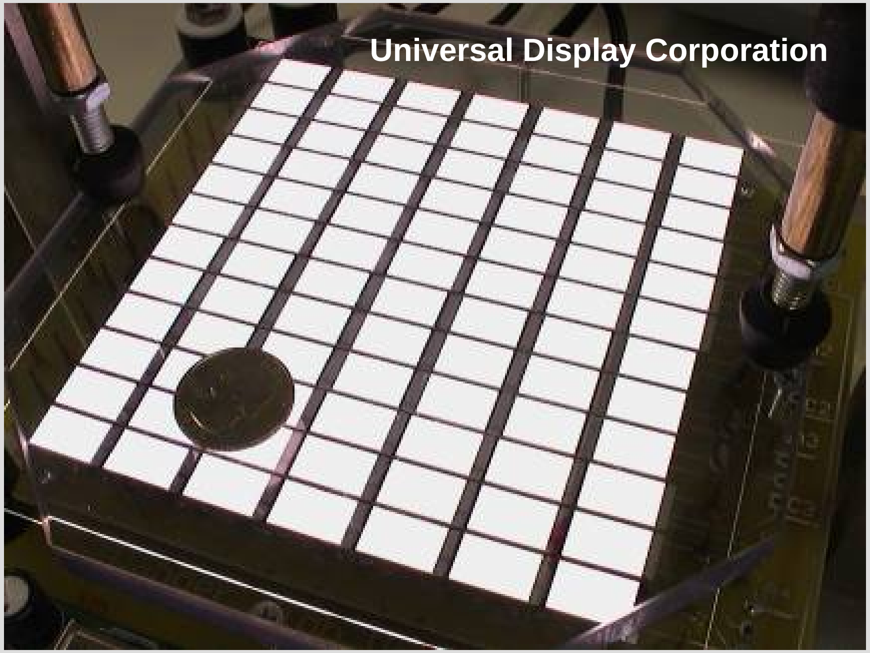
Big OLEDs may be in the Future…

OLED television
(Sony Corp.)

40” active matrix OLED panel
(Samsung)

Experimental Organic Lightbulbs

General Electric: 2 ft OLED panel

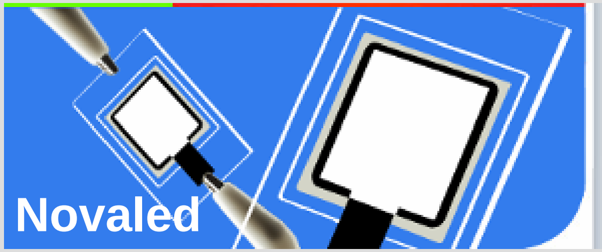


Universal Display Corporation

Note the lack of a luminaire,- these are large area, low intensity emitters)

Efficiency performance of OLED

- Showa Denko K.K.:single layer phosphorescent polymer OLEDs external quantum efficiency of 17% (green) and 16% (blue) with durability of 350,000 hours at 100 cd/m^2. They will build a trial volume-production line by the middle of this year.
- Novaled claims "groundbreaking" results with its p-i-n OLED technology.. White top emission devices achieved a lifetime of 18,000 hours at 3 V and 1,000 cd/m^2. Green top-emission OLEDs achieve 1,000 cd/m^2 at 2.5 V and 95 cd/A (about 110 lm/W) These green devices are based on Ir(ppy)$_3$.
- Universal Display Corporation achieved 30 lm/W at 1000 cd/m^2 (warm white).
- Osram: 25 lm/W white polymer devices
- Konica Minolta 60 lm/W, details unclear



Efficiency of Lighting System

- The **system efficiency is important**, not the bulb efficiency (i.e. bulb + voltage converter + luminaire)
  - Fluorescent lamp systems do not work anywhere near 80 lm/W (considering the ballast and luminaire losses).
  - OLEDs can operate directly from 115VAC and require no luminaire because they are a large area light source. This could be worth a factor of two in efficiency when comparing OLEDs to point source lamps (probably will require current regulation, though).
- High efficiency is only useful if consumers buy it.
  - Making square meters of OLED at a cost suitable for lighting is an unaddressed problem (all OLED manufacturing thus far is for displays).
- OLED lighting just looks different
  - There is value added in novelty (commercial, not necessarily energy)

Basic Research Needs for Solid State Lighting

Workshop Charge: To identify basic research needs and opportunities underlying light emitting diode and related technologies, with a focus on new or emerging science challenges with potential for significant long-term impact on energy-efficient and productivity-enhancing solid state lighting. Highlighted areas will include organic and inorganic materials and nanostructure physics and chemistry, photon manipulation, and cross-cutting science grand challenges.

Julia M. Phillips (Chair)
SNL

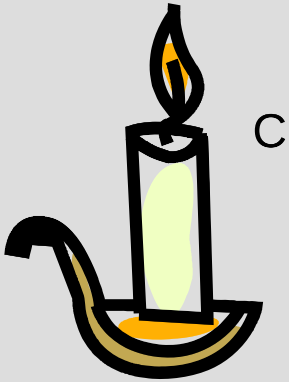
Paul E. Burrows (Co-Chair)
PNNL

BASIC RESEARCH NEEDS FOR
SOLID-STATE LIGHTING

Artificial lighting was among the first inventions of mankind…

Each subsequent improvement in lighting led to major lifestyle improvements

and improvements in the energy efficiency of the light



Candle: 0.05 lumens per watt

Gaslamp: 0.5 lumens per watt

“Incandescent” Lightbulb
15 lumens per watt
(5% efficient)

19th century, used that new-fangled electricity stuff

Why does lighting impact energy conservation?

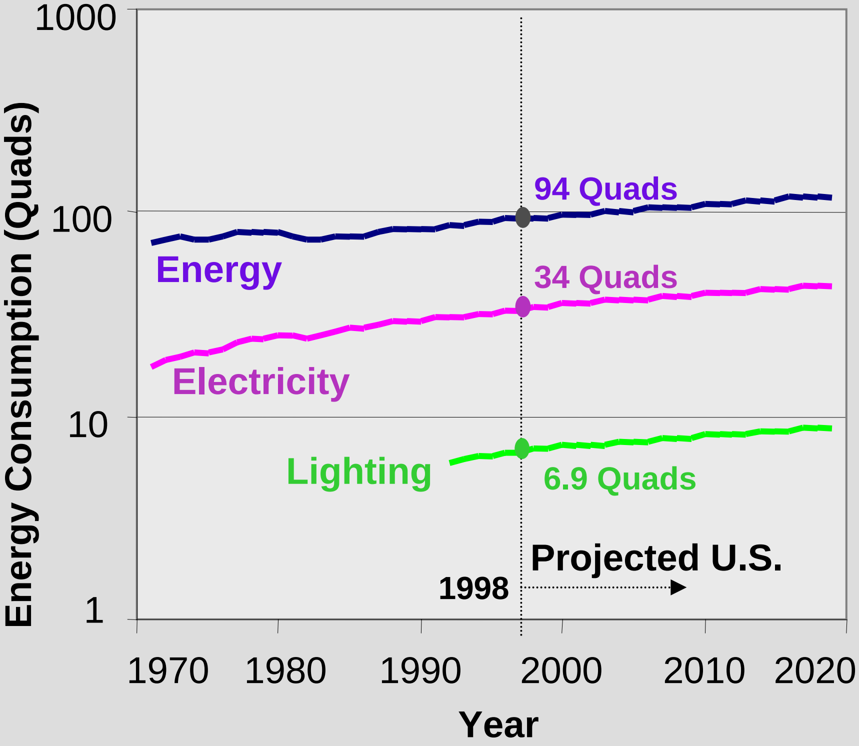
- Lighting consumes 22% of the electricity generated in the U.S.A.
- That's 8% of the total energy consumption
- Costs $50 billion per year
- Releases 150 million tons of CO_2 into the atmosphere each year
- Much of it is 19th century technology with poor efficiency

We should be able to do better

- **Lighting is a highly attractive target for reducing energy consumption!**

Efficiencies of energy technologies in buildings:

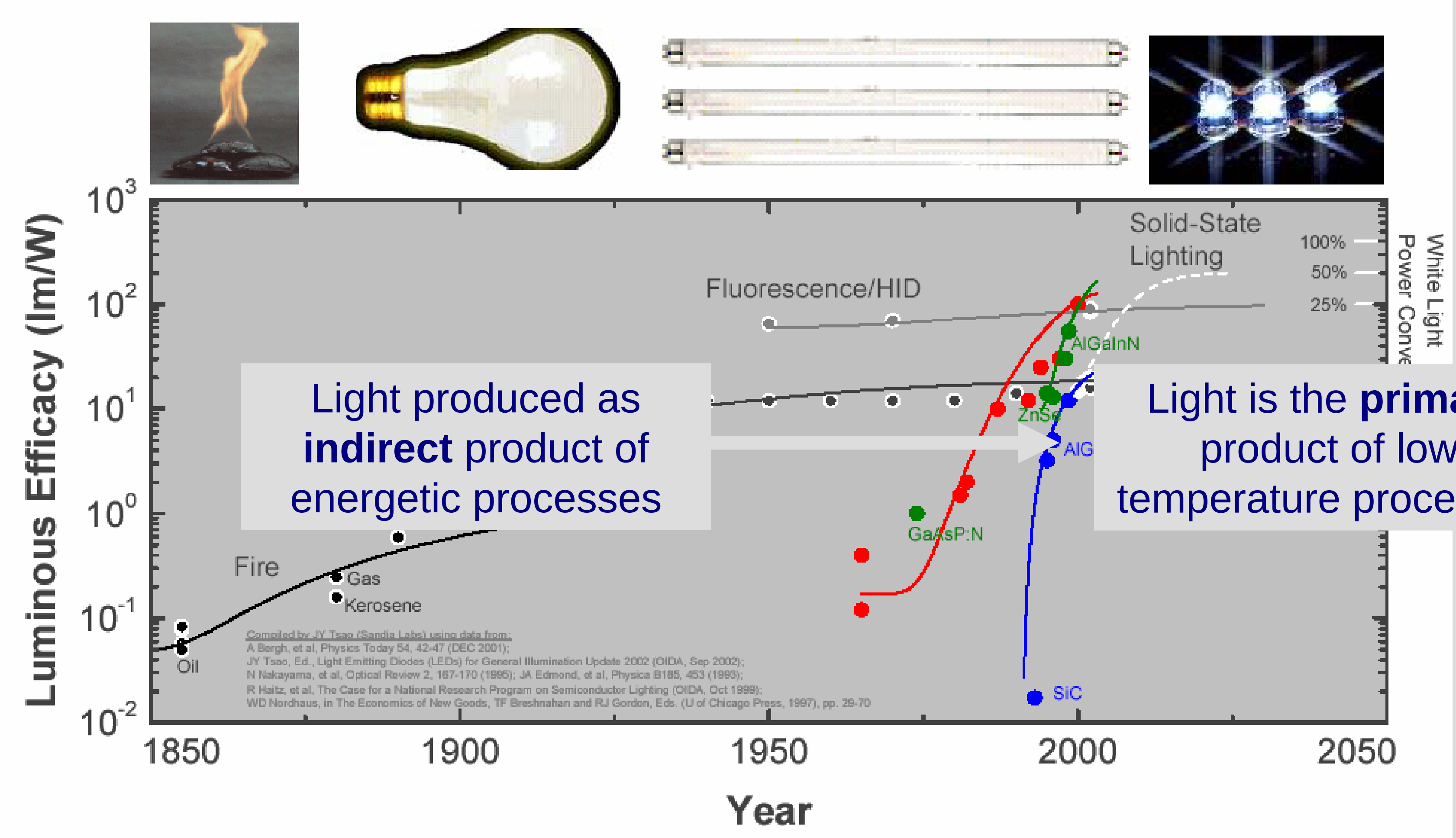
Heating:	70 - 80%
Elect. motors:	85 - 95%
Fluorescent:	**20%**
Incandescent:	**5%**



Battelle

Pacific Northwest National Laboratory
U.S. Department of Energy

Conventional Lighting is Limited



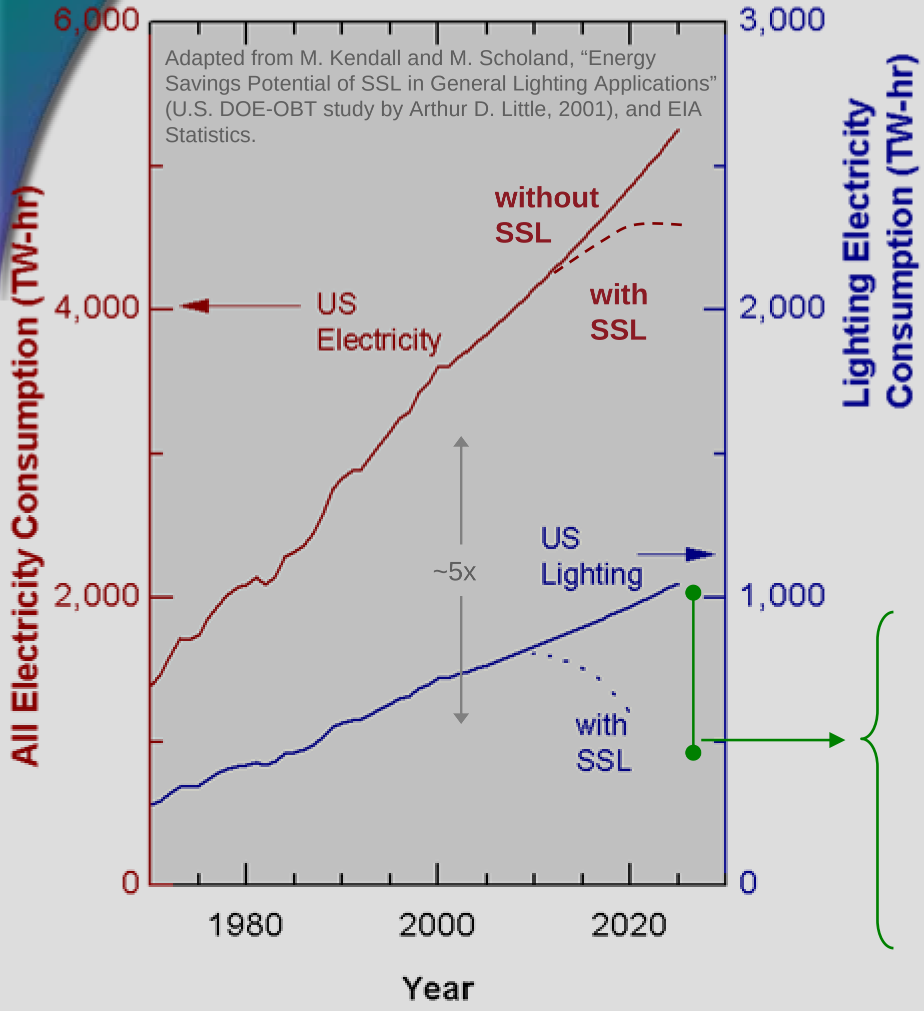
Compiled by JY Tsao (Sandia Labs) using data from:
A Bergh, et al, Physics Today 54, 42-47 (DEC 2001);
JY Tsao, Ed., Light Emitting Diodes (LEDs) for General Illumination Update 2002 (OIDA, Sep 2002);
N Nakayama, et al, Optical Review 2, 167-170 (1995); JA Edmond, et al, Physica B185, 453 (1993);
R Haitz, et al, The Case for a National Research Program on Semiconductor Lighting (OIDA, Oct 1999);
WD Nordhaus, in The Economics of New Goods, TF Breshnahan and RJ Gordon, Eds. (U of Chicago Press, 1997), pp. 29-70

Light produced as **indirect** product of energetic processes

Light is the **primary** product of low temperature processes

Energy Efficiency: Solid-state lighting is potentially **10X and 2X more efficient** than incandescent and fluorescent lamps, respectively.

Effects of widespread adoption of 50% efficient SSL


Adapted from M. Kendall and M. Scholand, "Energy Savings Potential of SSL in General Lighting Applications" (U.S. DOE-OBT study by Arthur D. Little, 2001), and EIA Statistics.

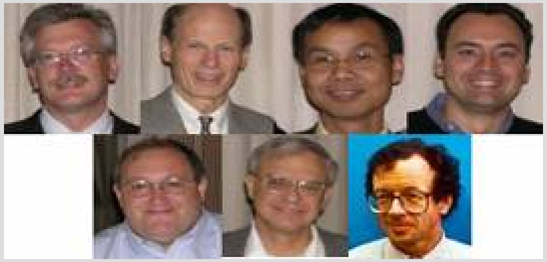
- SSL has the potential, by 2025, to:
  - decrease electricity consumed by lighting by 62%
  - decrease total electricity consumption by 13%

Projected Year 2025 Savings	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

Basic Research Needs for Solid State Lighting

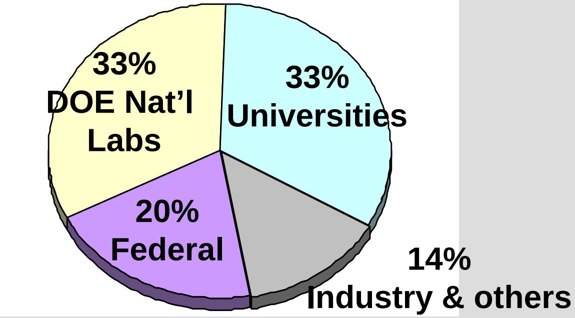
May 22-24, 2006

Workshop Chairs: Julia Phillips (Sandia National Labs)
Paul Burrows (Pacific Northwest National Lab)



	Science Panel Chairs:
LED:	Jerry Simmons (SNL)
	Bob Davis (Carnegie Mellon U)
OLED:	Franky So (U of Florida)
	George Malliaras (Cornell)
Cross-Cutting:	Jim Misewich (BNL)
	Arto Nurmikko (Brown U)
	Darryl Smith (LANL)

Total 79 participants

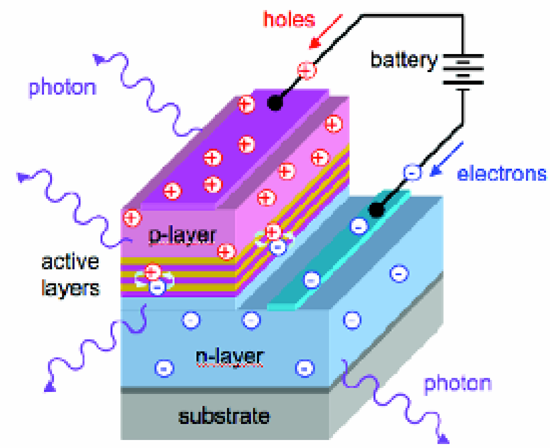


Charge: identify transformational science
Output: www.sc.doe.gov/bes/reports/list.html

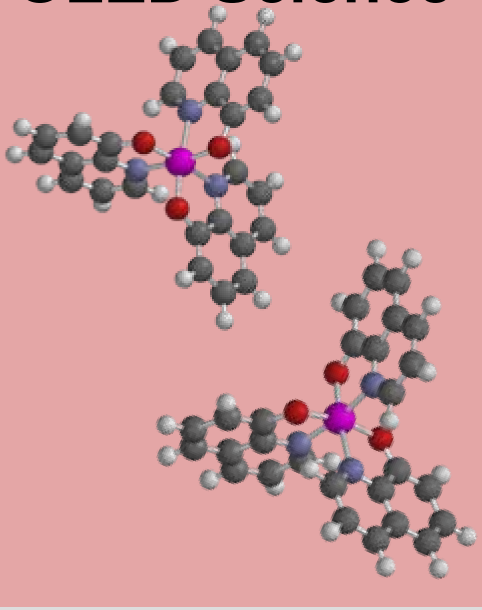
Workshop Panel Structure

- The workshop highlighted
  - 12 Priority Research Directions (PRDs), each specific to an individual panel
  - 2 Grand Challenges (GCs) which overarch all panel

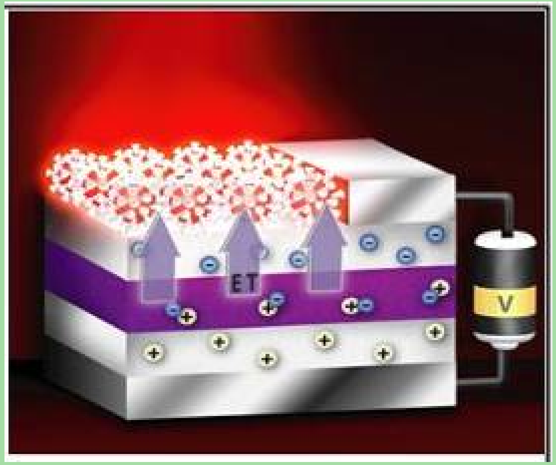
LED Science



OLED Science



Cross-cutting Science



From Science to Deployment – a map for Solid-State Lighting

Discovery Research

- Rational design of SSL lighting structures
- Control of radiative & non-radiative processes in light-emitting materials
- New functionalities through heterogeneous nanostructures
- Innovative photon management
- Enhanced light-matter interactions
- Precision nanoscale characterization, synthesis, and assembly
- Multi-scale modeling – quantum excitations to light extraction

Use-inspired Basic Research

- Unconventional light-emitting semiconductors
- Photon conversion materials
- Polar materals and heterostructures for SSL
- Luminescence efficiency of InGaN
- Managing and exploiting disorder in OLEDs
- Understanding degradation in OLEDs
- Integrated approach to OLED fundamentals

Office of Science
BES

Applied Research

Technology Milestones:

By 2025, develop advanced solid state lighting technologies with a product system efficiency of 50 percent with lighting that accurately reproduces sunlight spectrum.

- Materials and components for inorganic and organic light-emitting diodes research for improved efficiency and cost reduction
- Strategies for improved device light extraction
- Low-cost fabrication and patterning techniques and tools & manufacturing R&D
- Product degradation and reliability issues

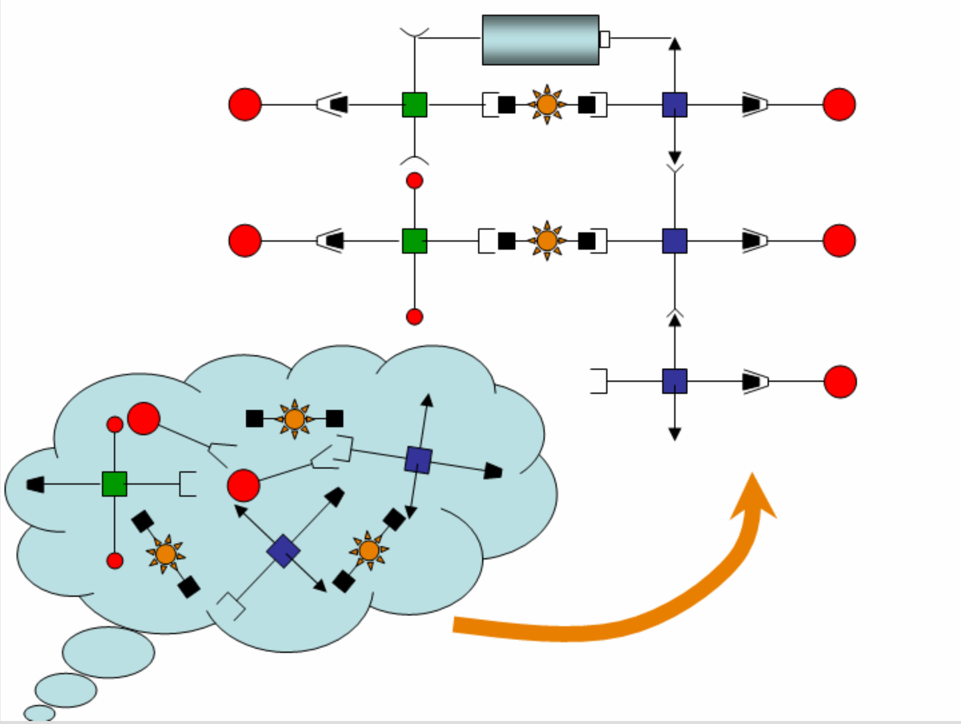
Technology Maturation & Deployment

- Developing national standards and rating systems for new products
- Commercial adoption and support
- Industrial partnership
- Legal, health, market, and safety issues
- Cost reduction
- Prototyping

Technology Offices
EERE

GRAND CHALLENGE 1:
Rational design of solid-state lighting structures

Today, light-emitting solid state materials are discovered rather than designed.

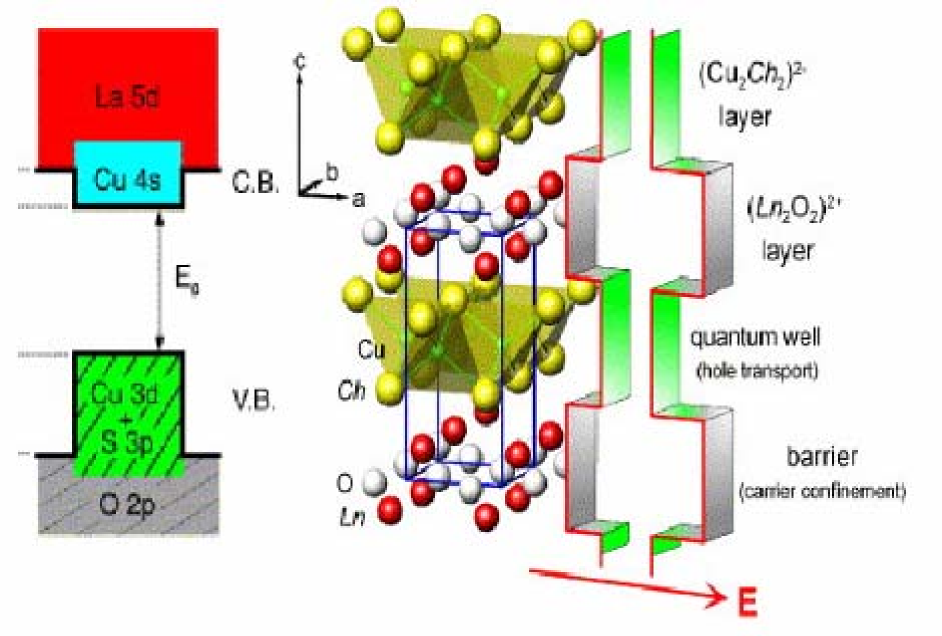


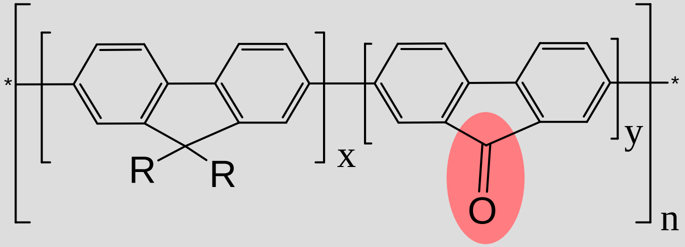
The CHALLENGE:

Can we design optimized device components that assemble into a high efficiency charge-to-light conversion system?

Rational design of solid-state lighting materials

- Novel oxychalcogenide materials have shown wide, direct bandgap behavior:
  - How do we design other such materials?
  - Multiscale theory and modeling to predict optimal structure
  - Fabrication of materials and structures designed to optimize properties:
    - Optical
    - Transport
- Design of organic light emitting materials
  - Design of charge transport properties, spin-orbit coupling, etc.

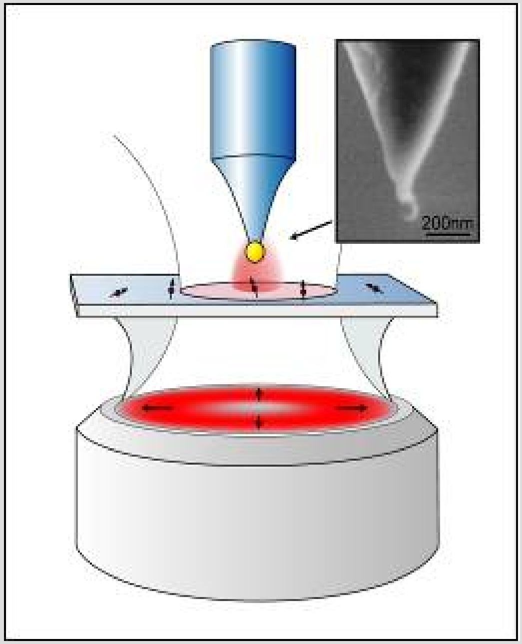


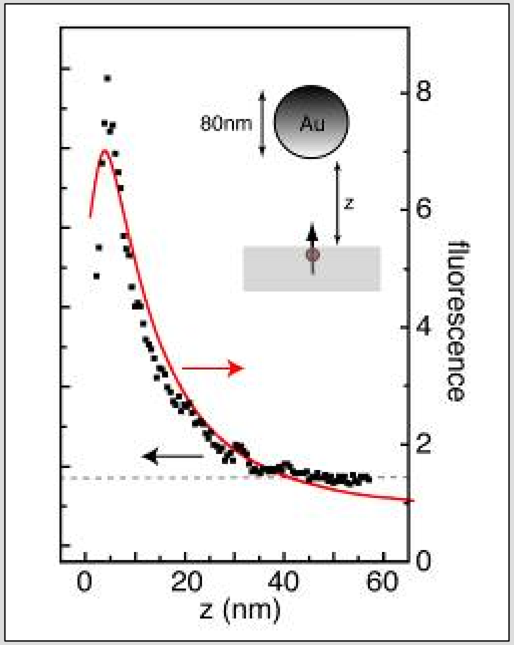


GRAND CHALLENGE 2: Control of radiative and nonradiative processes in light-emitting materials

Light-emitting efficiency is determined by competition between radiative and non-radiative processes.

The CHALLENGE:
Can we understand and control the physics of photon generation and emission?





Control of radiative and non-radiative processes in light-emitting materials

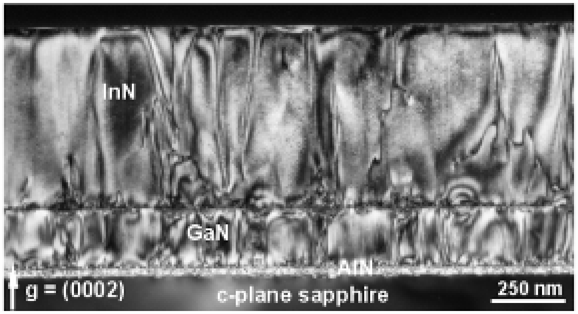
<ins>Science questions and opportunities</ins>

What limits the electroluminescence efficiency of inorganic and organic semiconductor LEDs? What is the role of:

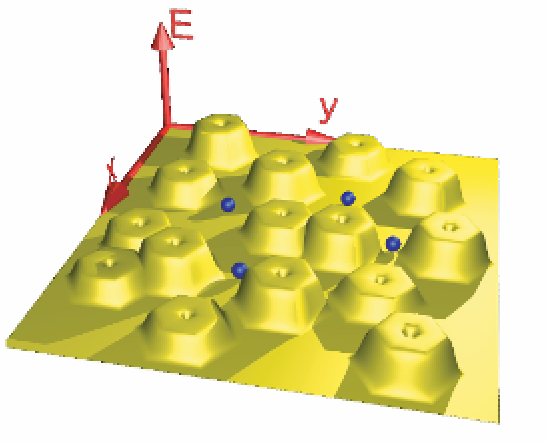
- extended and point defects (e.g. InGaN)
- polarization fields
- material inhomogeneities

Can we tailor defect and nanostructures for higher efficiencies?

Can we enhance radiative rates through deliberate modulation of the photonic density of states?



J. Jasinski and Z. Liliental-Weber



Example “big questions” for OLED Workshop report, Appendix 5

- Why are organic phosphors limited to a radiative lifetime > 0.5μs and what is the lower limit?
- How do impurities affect device efficiency and lifetime and how can we assay to the accuracy required to answer such questions?
- Can we engineer air-stable organics and injecting cathodes?

Applications driven but fundamental science questions

Summary

New lighting technology is "low-hanging fruit" in the drive for energy efficiency

- *Increase efficiency by 10X*

Extrapolations of current technologies will not meet this goal

- *Old technologies; fundamental limits*

Solid-state lighting can transform the way we light the world

Success requires:

- *Fundamental understanding to optimize current SSL approaches*
- *Discovery research to reveal the basis for breakthrough efficiencies*

SSL research will also drive discoveries in photon-matter interactions, new materials/structures, and new tools/methods

BASIC RESEARCH NEEDS FOR
SOLID-STATE LIGHTING

www.sc.doe.gov/bes/reports/list.html