BES UPDATE

Fundamentals at the Nanoscale

2007 DOE SOLID STATE LIGHTING WORKSHOP

1 February 2007

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Change a Light, Change the World

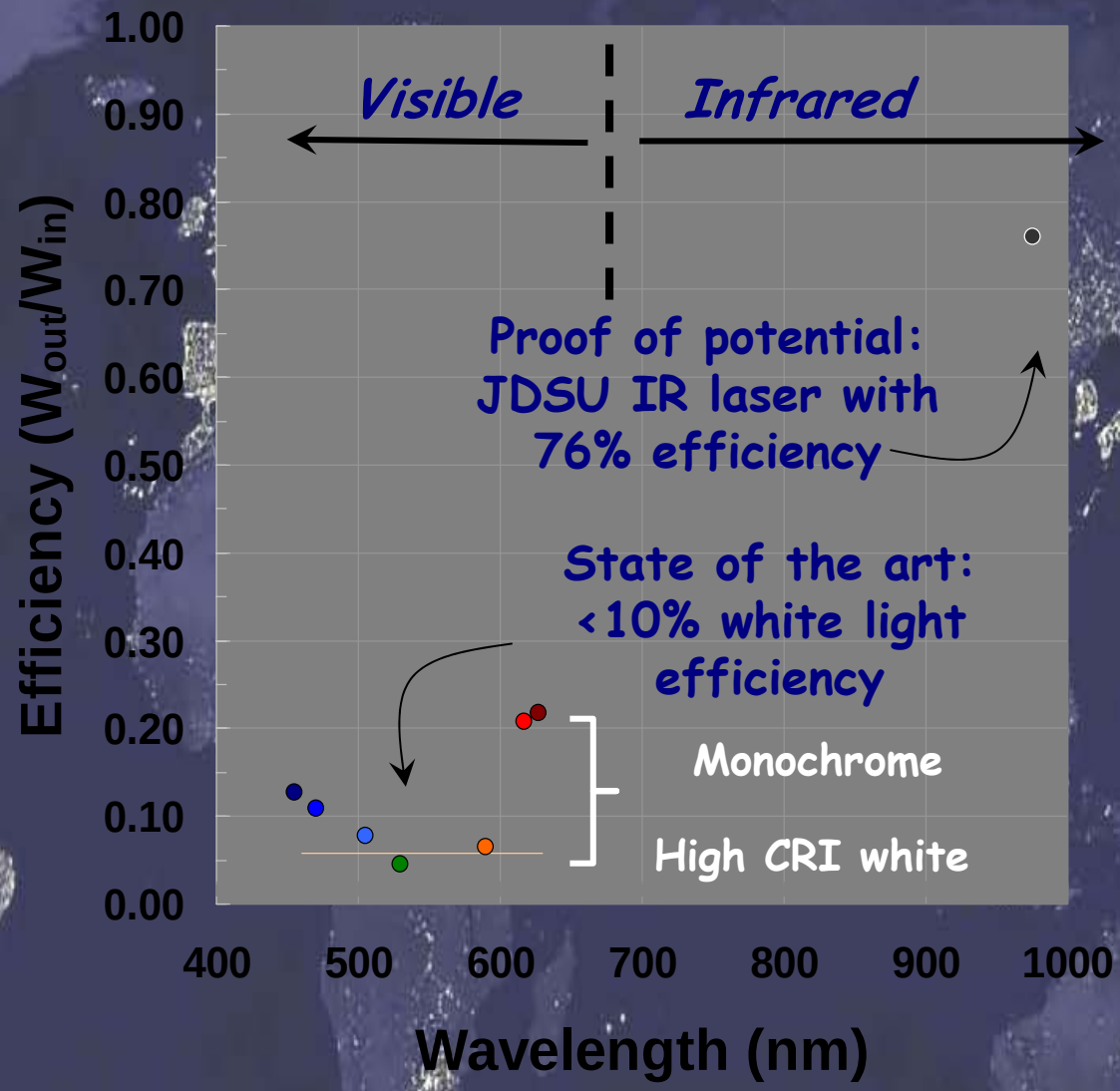
- The century old, low conversion efficiency technologies still dominate world lighting application.
- Semiconductor based Light Emitting Diodes offer the potential for significant savings in energy consumption. Organic LEDs or OLEDs offer potential ease of processing with challenges inherent in the complex nature of the materials.
- Nanoscale basic research presents new opportunities for fundamental understanding that will advance solid-state lighting technologies.

Basic Energy Sciences
Serving the Present, Shaping the Future

Acknowledgments:
DOE-EERE Building Technologies Program: Jim Brodrick; Univ of Utah: Valy Vardeny; UCSB: Alan Heeger; GE: Anil Duggal; SNL: Jeff Tsao, Jerry Simmons, Julia Phillips; LANL: Darryl Smith; PNNL: Paul Burrows

Why we need a breakthrough

While the recent progress in solid state lighting efficiency is impressive, it is dwarfed by the chasm that remains to be crossed!



BASIC ENERGY SCIENCES -- Serving the Present, Shaping the Future

The Mission:

- Advance the frontiers of knowledge to provide the scientific foundations for new and improved, environmentally conscientious energy technologies
- Create and operate forefront scientific user facilities
- Provide innovative and effective research teams and tools
- Energy Policy Act of 2005. Section 975 SOLID STATE LIGHTING. The Secretary shall conduct a program of fundamental research on solid state lighting in support of the Next Generation Lighting Initiative carried out under section 912.
- Scientific and Technical Core Competencies:
- Materials sciences and engineering; chemistry; geosciences; physical biosciences
- Multidisciplinary nanoscale science and technology
- Reactor and accelerator based user facilities for photon, neutron, and electron beam scattering research
- Advanced instrumentation

Outline

- BES Contractors Meeting
- BES Workshop: Basic Research Needs for Solid State Lighting
- Program Outlook

BES Contractors Meeting

- Colocated with **Solid-State Lighting Program Planning Workshop** last year.
- Thanks to SSL program for the kind invitation to participate, logistical & meeting support
- Recognize Prof. Valy Vardeny (Univ. Utah) for his assistance in leading the Contractors meeting
- Featured ~ dozen PI presentations, 2 invited speakers, and a dozen and a half poster presentations

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
SNL

Paul E. Burrows
PNNL

Basic Research Needs for Solid State Lighting

May 22-24, 2006

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

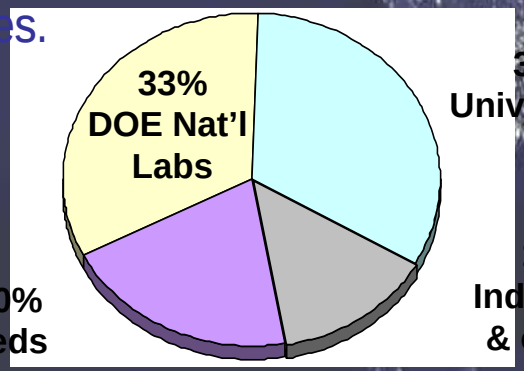
Panel Chairs:

LED Science: Jerry Simmons (SNL)
Bob Davis (Carnegie Mellon U)

OLED Science: Franky So (U of Florida)
George Malliaras (Cornell)

Cross-Cutting Science: Jim Misewich (BNL)
Arto Nurmikko (Brown U)
Darryl Smith (LANL)

Total 79 participants from academia, DOE National Labs, BES and other federal agencies, industries, and foreign countries.



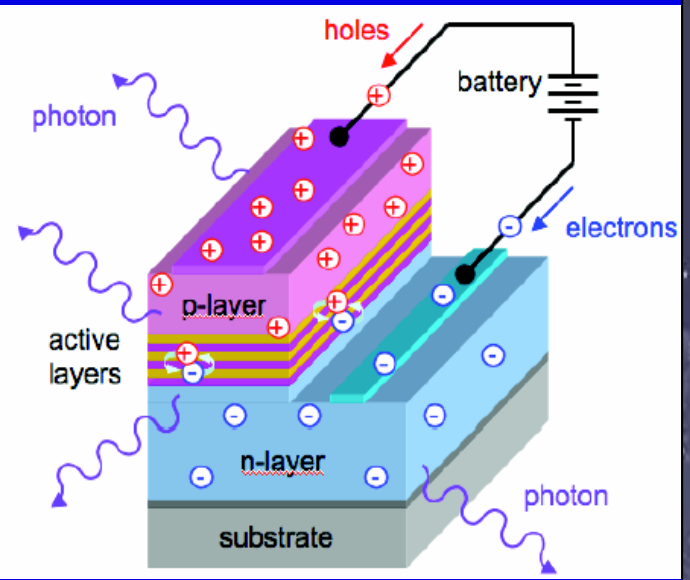
Plenary Speakers:

P. Dehmer (BES), J. Brodrick (DOE-EERE), Fred Schubert (RPI), George Craford (Lumileds) Alan Heeger (UCSB), Eli Yablonovitch (UCLA)

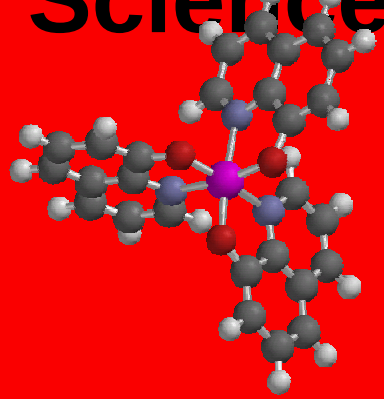
Workshop Coordinator: Jeff Tsao (SNL- on Detail to DOE/BES)

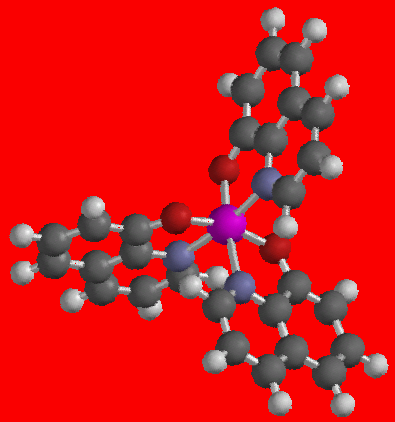
The panels

LED Science

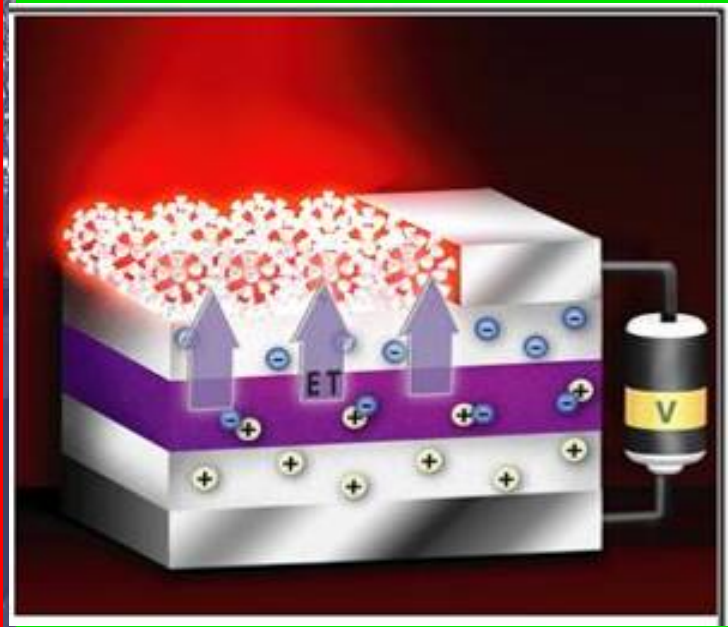


OLED Science





Cross-cutting Science



Panel structure and output

Science Grand Challenges (2)

More challenging, riskier and longer term, requiring development of tools and techniques which do not currently exist and would change the way we think about converting power to light… may bridge several PRDs

Panel 1 LED Science	Panel 2 OLED Science	Panel 3 Crosscutting Science
Survey: Status of Field	Survey: Status of Field	Survey: Status of Field
Priority Research Direction(4)	Priority Research Direction(3)	Priority Research Direction(5)

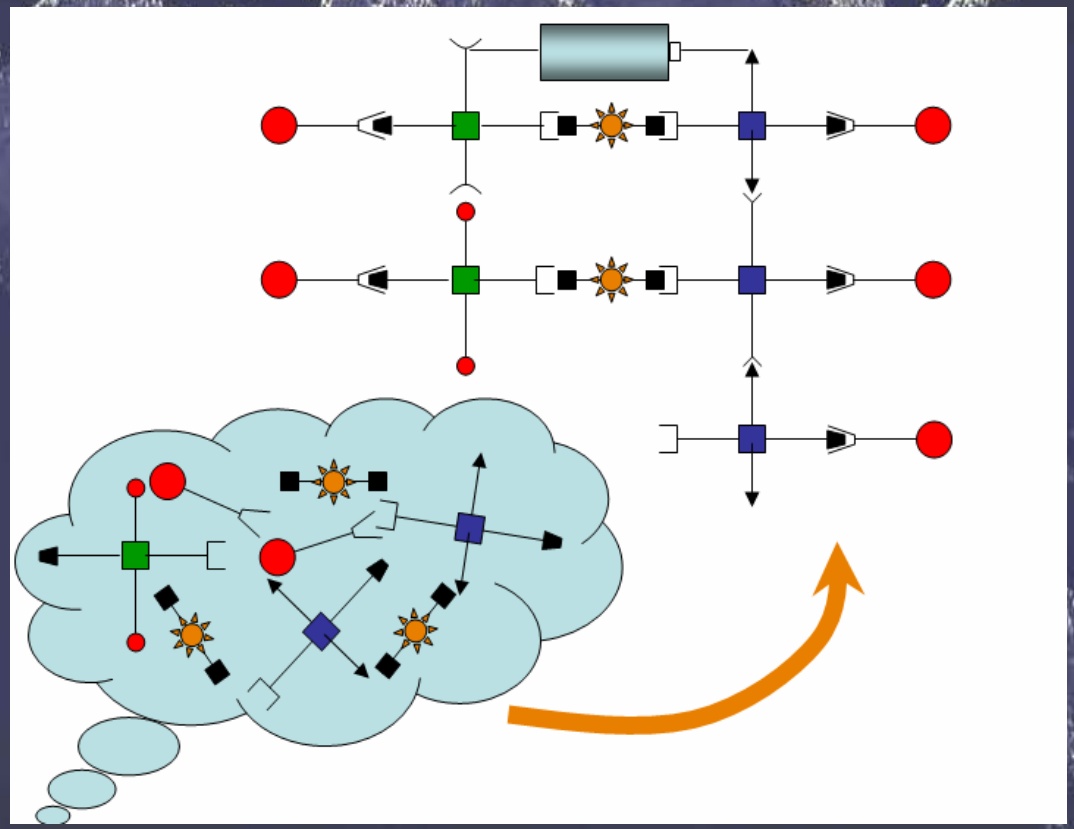
New breakthroughs in understanding or instrumentation that would solve roadblocks specific to the aims of the panel

GRAND CHALLENGE:
Rational design of solid-state lighting structures

Light-emitting solid state materials are discovered rather than designed today.

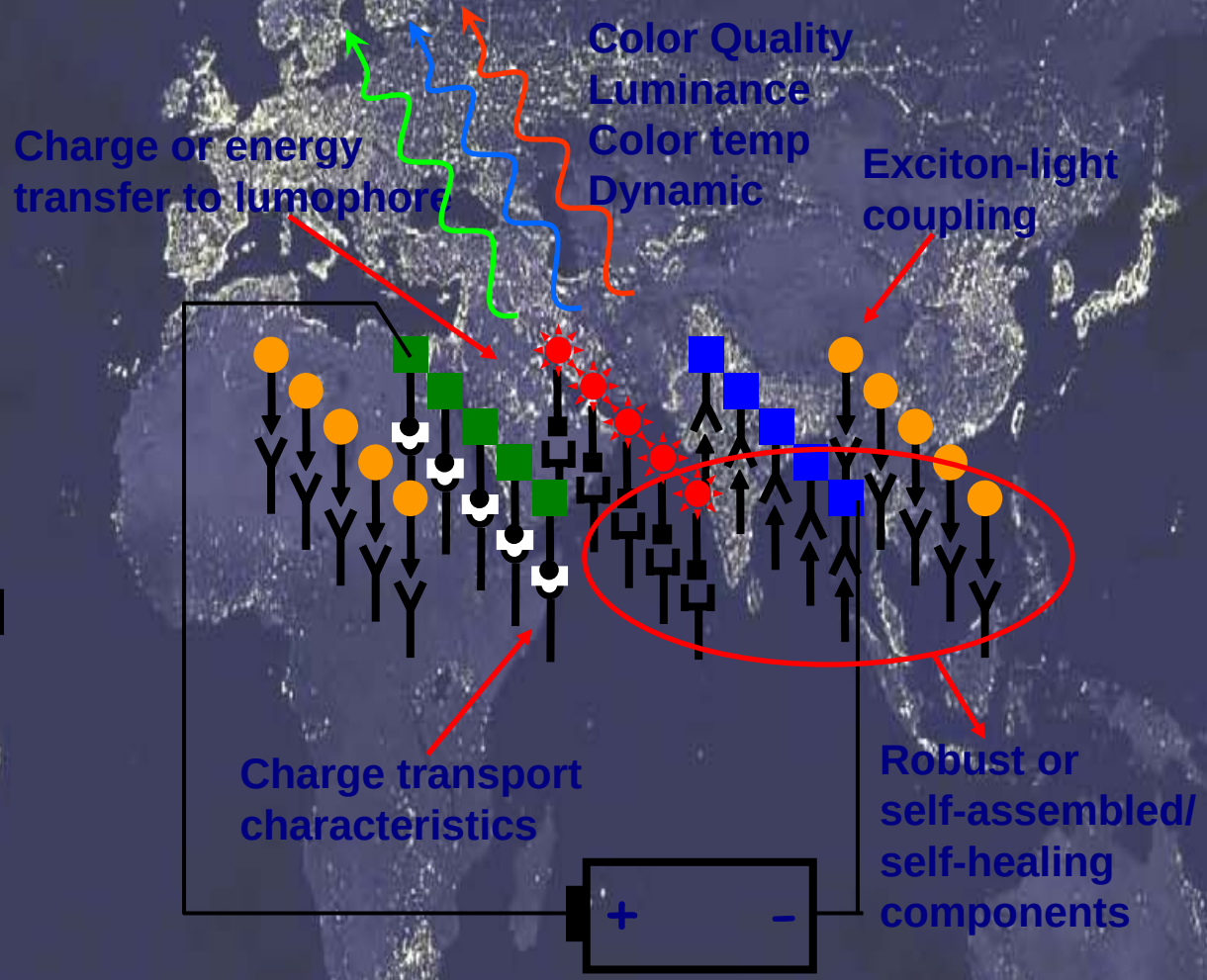
The CHALLENGE:

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



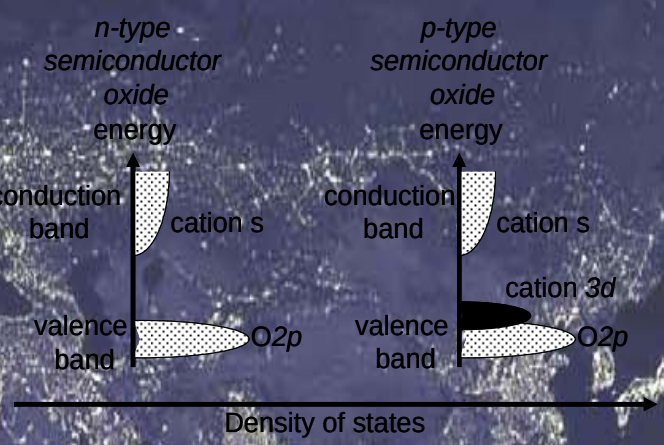
Rational design of solid-state lighting structures

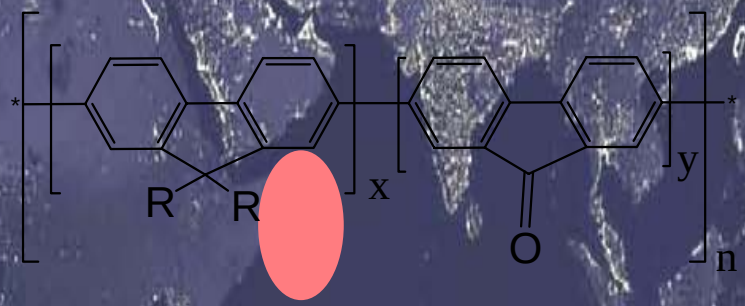
- Achieve optimized efficiency through:
  - Multiscale theory and modeling to predict optimal structure
  - Fabrication of materials and structures designed to optimize properties:
    - Optical
    - Transport

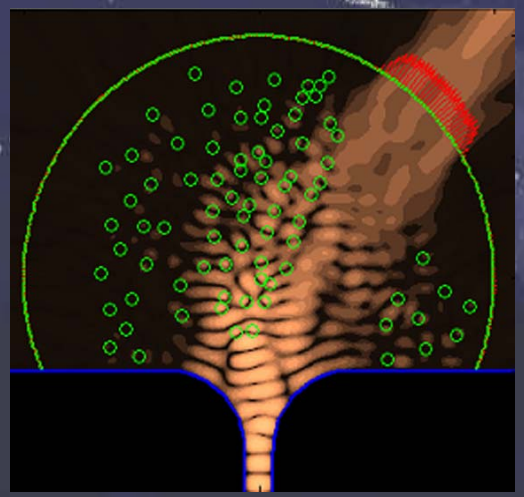


Rational design of solid-state lighting structures

- Fundamental materials science needs
  - Physics: ability to precisely tune basic physical properties
  - Chemistry: high-quality materials, high precision placement
  - Theoretical understanding







Grand Challenge #1 & associated Priority Research Directions

Discovery Research	Use-inspired Basic Research	Applied Research	Technology Maturation & Deployment
▪ Rational design of SSL lighting structures	▪ Unconventional light-emitting semiconductors ▪ Photon conversion 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	▪ Managing and exploiting disorder in OLEDs ▪ Understanding degradation in OLEDs		

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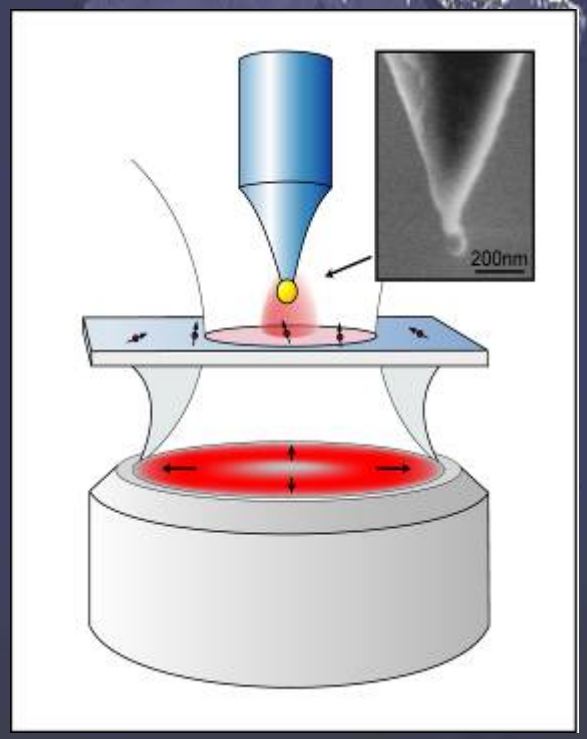
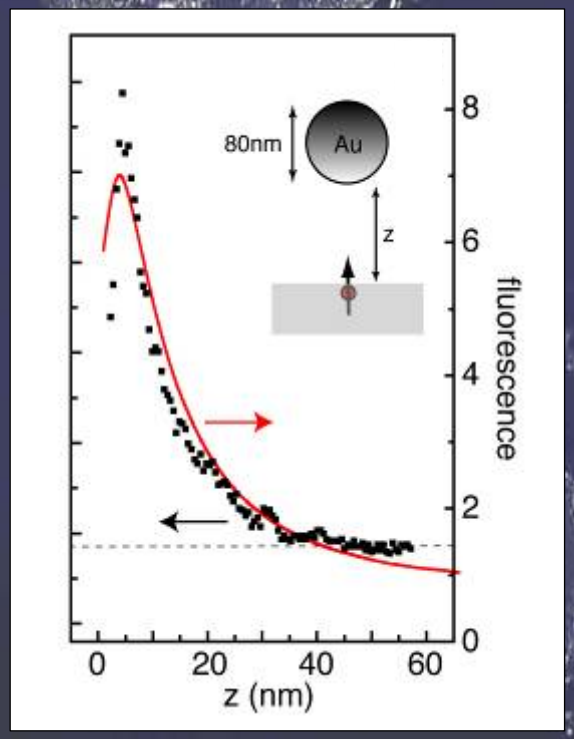
GRAND CHALLENGE: Control of radiative and nonradiative processes in light-emitting materials

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

<u>The CHALLENGE:</u>
Can we understand and control the physics of photon generation and emission?



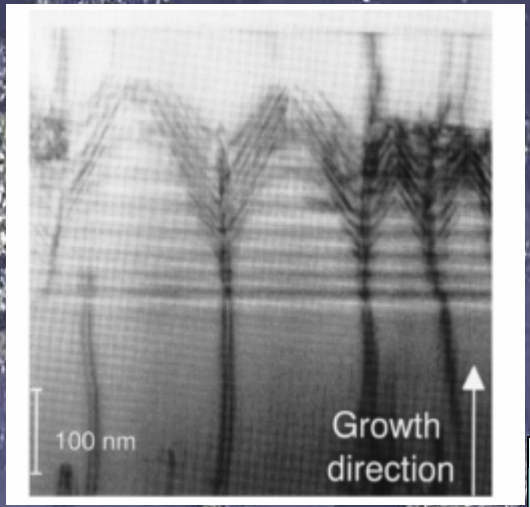


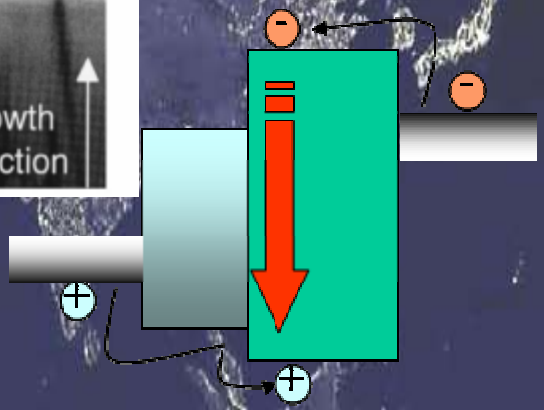
Control of radiative and non-radiative processes in light-emitting materials

Overview

How does radiative and non-radiative recombination depend on:

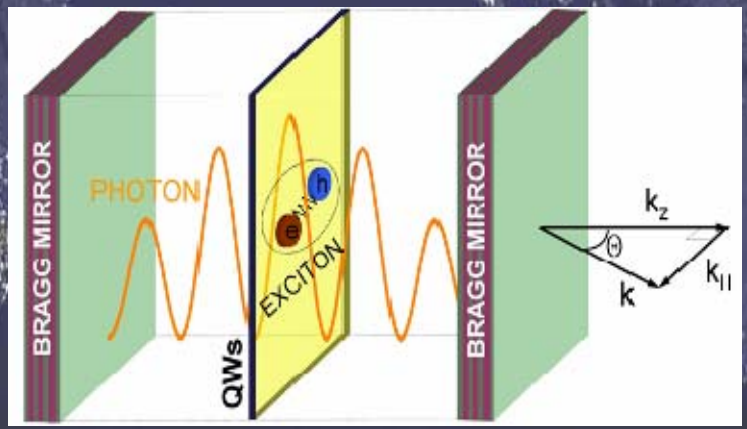
- **Materials microstructure**
- **Point and extended defects**
- **Charge carrier transport**
- **Localization and screening**
- **Polarization and piezoelectric fields**
- **Alloy composition and compositional variations**
- **Spin-orbit coupling**





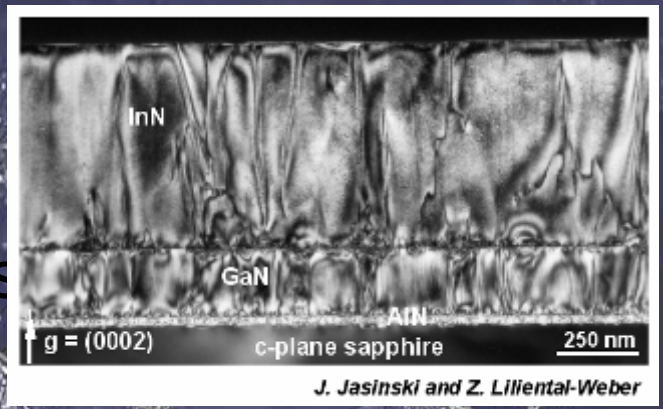
Can we understand and selectively engineer radiative and non-radiative pathways for enhanced optical efficiency through:

- **Defect engineering**
- **Implementation of advanced light-matter interaction concepts**



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

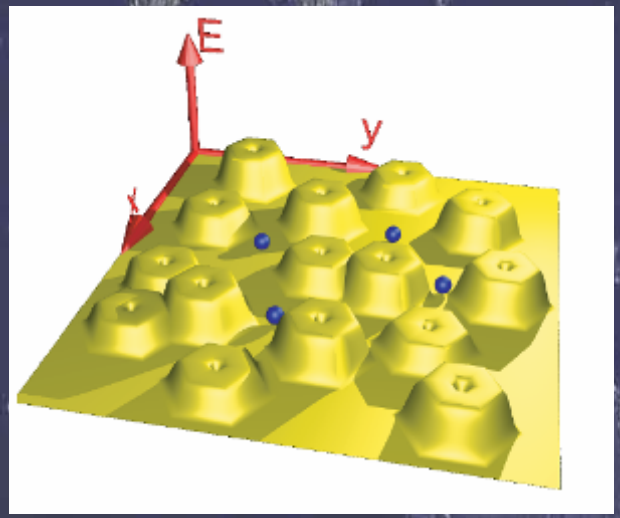
Science questions and opportunities



J. Jasinski and Z. Liliental-Weber

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

- extended and point defects
- 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?

Grand Challenge #2 and associated Priority Research Directions

Discovery Research	Use-inspired Basic Research	Applied Research	Technology Maturation & Deployment
	▪ Unconventional light-emitting semiconductors		
▪ Control of radiative & non-radiative processes in light-emitting materials			
	▪ Polar materials and heterostructures for SSL ▪ Luminescence efficiency of InGaN ▪ Managing and exploiting disorder in OLEDs		
▪ Precision nanoscale characterization, synthesis, and assembly			
	▪ Integrated approach to OLED fundamentals		

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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 materials and heterostructures for SSL
- Luminescence efficiency of InGaN
- Managing and exploiting disorder in OLEDs
- Understanding degradation in OLEDs
- Integrated approach to OLED fundamentals

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

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Technology Offices
EERE

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*

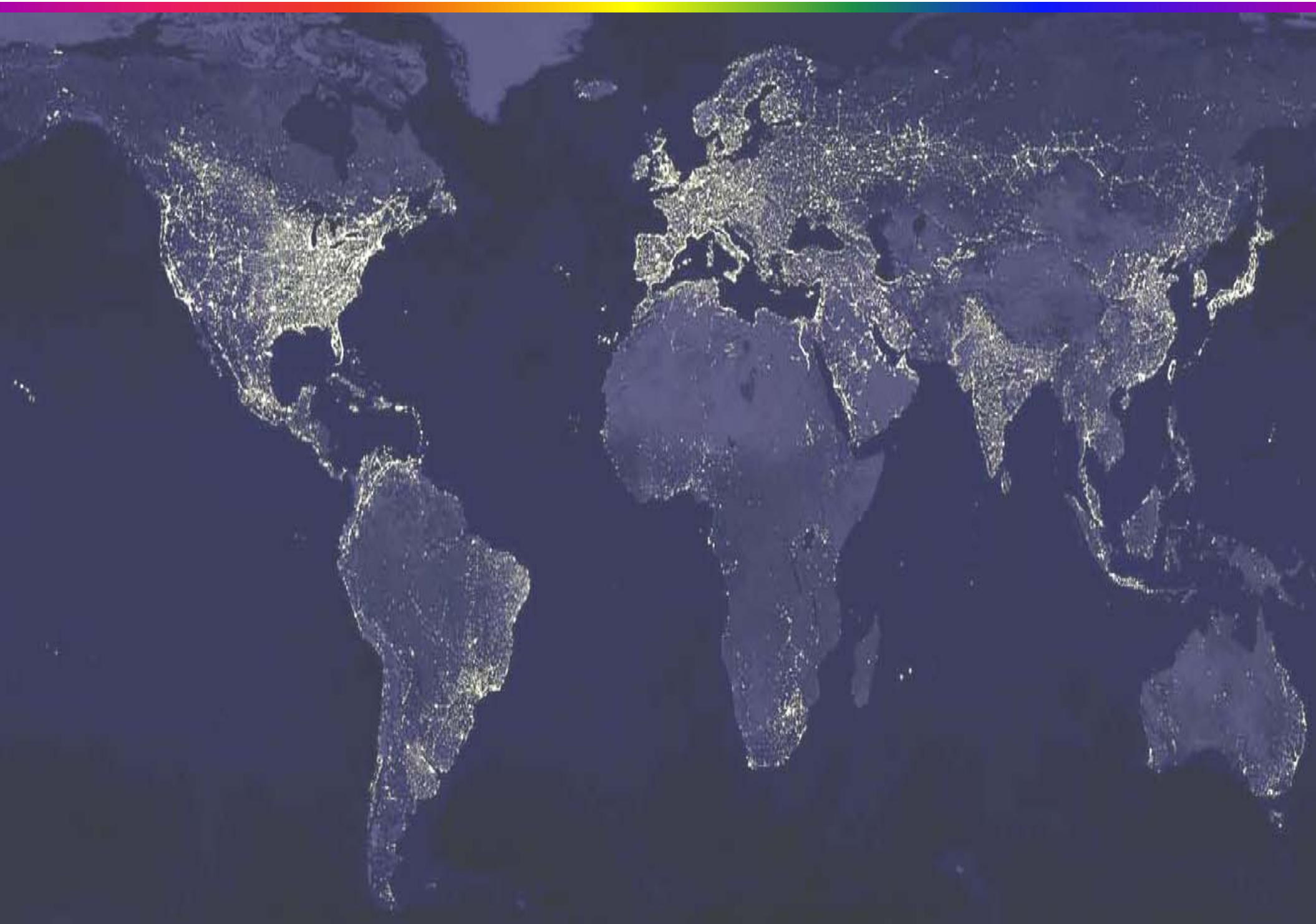
Solid-state lighting can transform the way we light the world

Success requires:

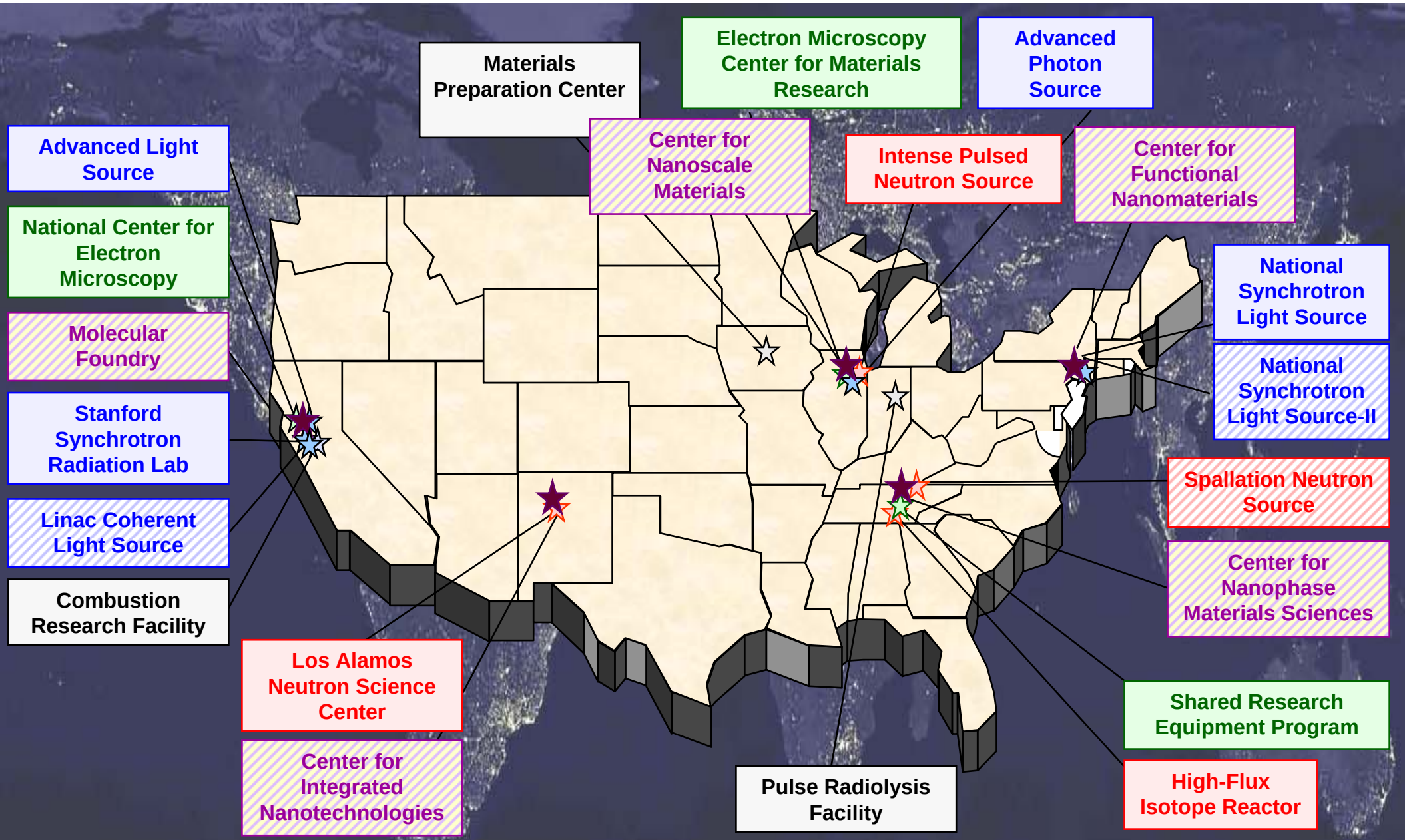
- *Fundamental understanding to optimize current SSL approaches*
- *Discovery research to reveal the basis for breakthrough efficiencies*

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

BES OUTLOOK



BES Scientific User Facilities Serve ~10,000 Users Each Year



- 4 Synchrotron Radiation Light Sources
- Linac Coherent Light Source (Under construction)
- 4 High-Flux Neutron Sources (SNS under construction)
- 3 Electron Beam Microcharacterization Centers
- 5 Nanoscale Science Research Centers (Under construction)
- 3 Special Purpose Centers

BES National User Facilities for Nanoscale Science– Actual Photos

Center for Functional Nanomaterials (Brookhaven National Laboratory)

Center for Nanoscale Materials (Argonne National Laboratory)

Molecular Foundry (Lawrence Berkeley National Laboratory)

Center for Nanophase Materials Sciences (Oak Ridge National Laboratory)

Center for Integrated Nanotechnologies (Sandia & Los Alamos National Labs)

LED Research Advancements and Opportunities

New Materials

New Classes of Light Emitters:

AlInGaP – Red, Yellow InGaN – Blue, Green

Lattice Matched Substrates

Semiconductor Nanomaterials and Nanostructures

Thin Film and Bulk Crystal Growth, Self-Assembly

UV-Stable Packaging / Encapsulant Materials

Photon Creation

Interplay between Electron-hole Injection and Recombination, Band Structure, Defects, Impurities, and Strain

Photon Extraction

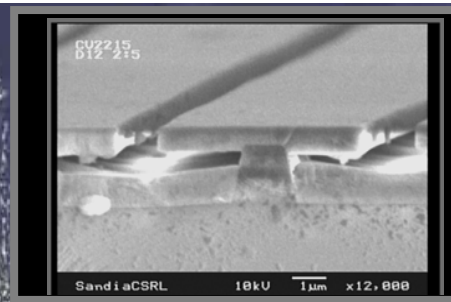
Manipulation of Optical Modes by use of Optical Microcavities and Photonic Lattices

3D Nanostructuring, Surface Plasmons

Photon Wavelength Conversion

New Phosphors – New Material Families and Nanoscience Approaches

New Approaches to Optical Index Matching and Photon Guiding



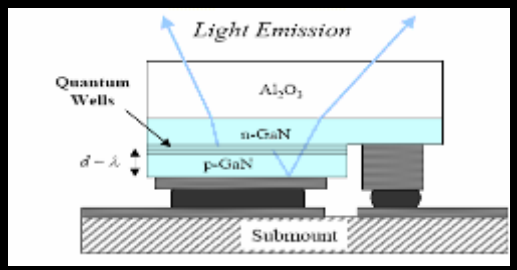
Cantilever epitaxy reduces defect density in GaN

J. Simmons et al., SNL

Nanoscale Indium clustering in InGaN

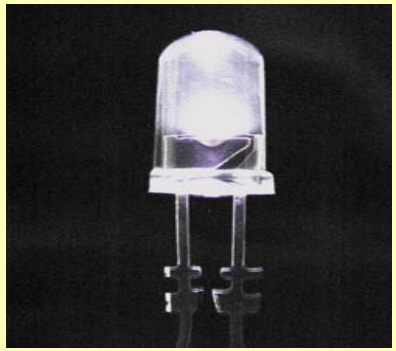
LBNL and Lumileds CRADA, NCEM HRTEM image

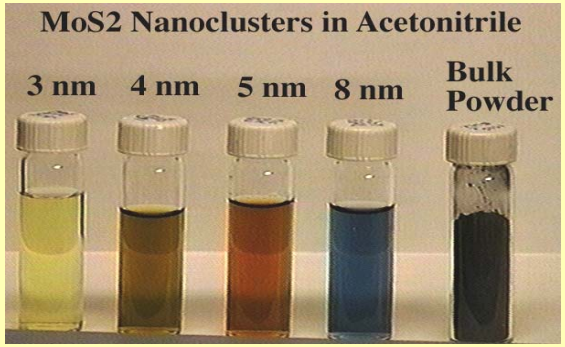
2.8 nm InGaN Quantum Well



Microcavity effects for increased light extraction

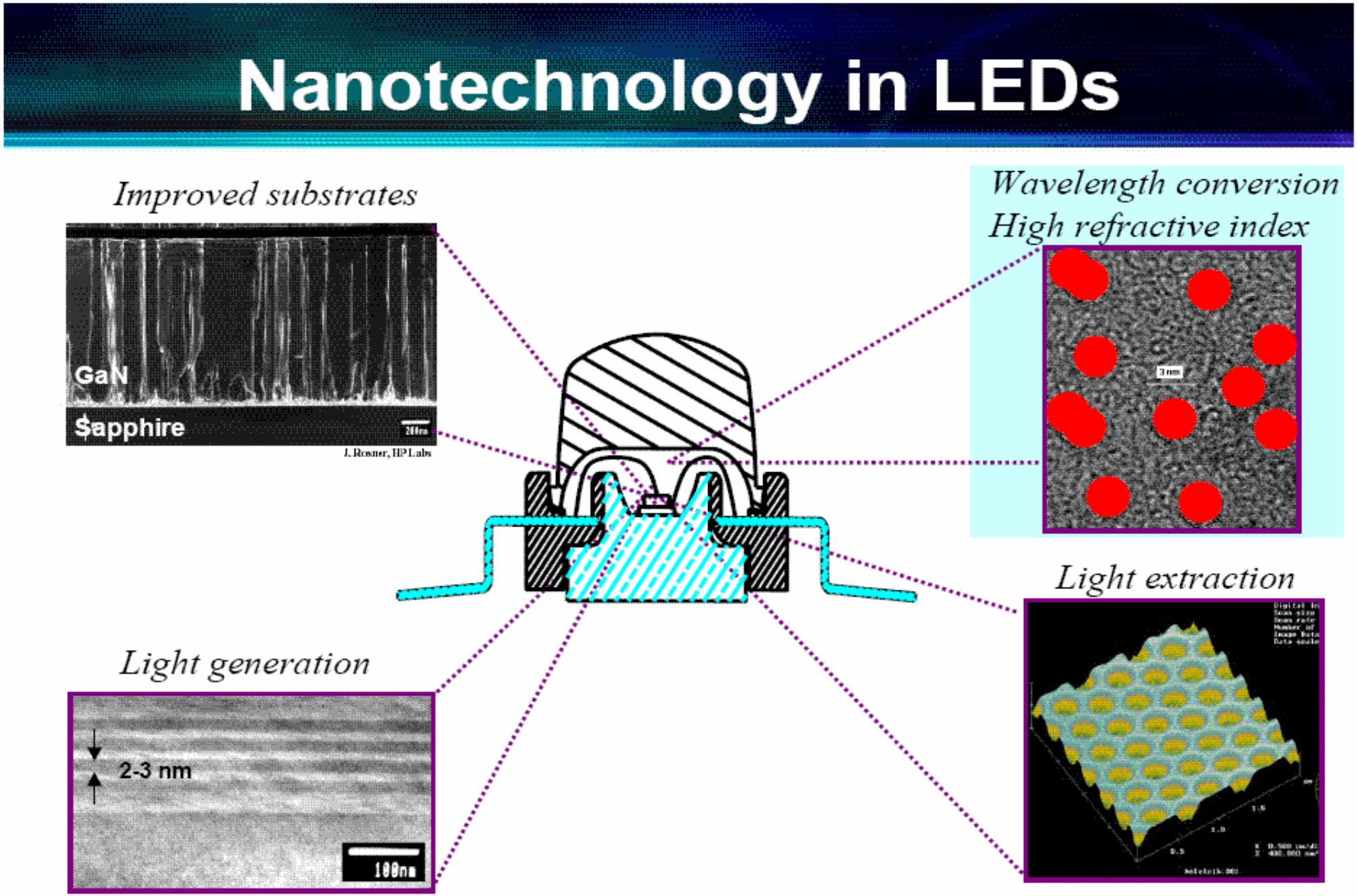
Shen et. al., *Appl. Phys. Lett.* 82, 2221 (2003).





Nano quantum dots provide tunable phosphors

Nanotechnology-Enabled LED Research Breakthroughs



quantum well structure

Source: G. Craford, Lumleds, 2004 DOE Nanosummit

Nanoscale Research Opportunities in OLEDs

1. Organic Semiconductors

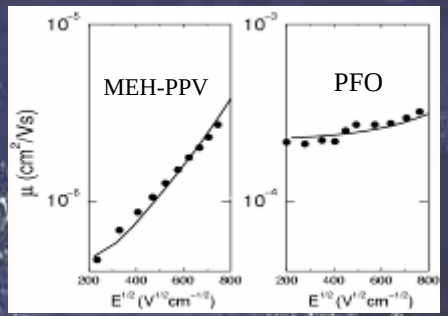
Defect Tolerant

The Wonders of Chemistry-

Guided by Quantum Chemistry and Intuition

Widely Tunable Properties

Semiconducting and metallic polymer "inks" A. Heeger, UCSB

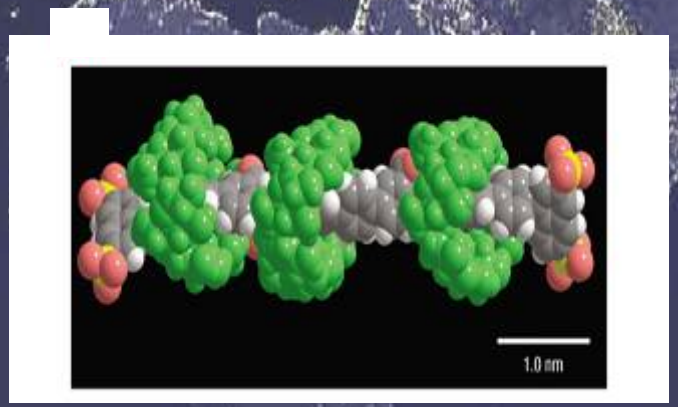


Mobilities Modeling
D. Smith, LANL

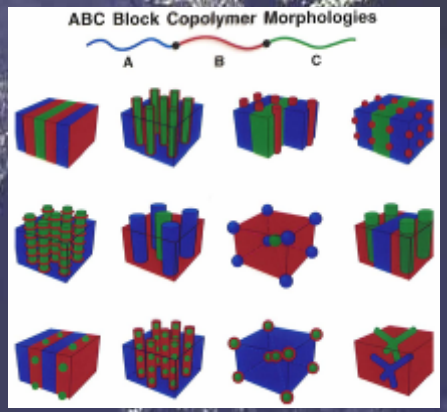
2. Synthesis and Processing

Solution and Vacuum Processing

Self Assembly at the Molecular Level



Chemical structures of the polyrotaxanes
Cacialli et al, Nature Materials



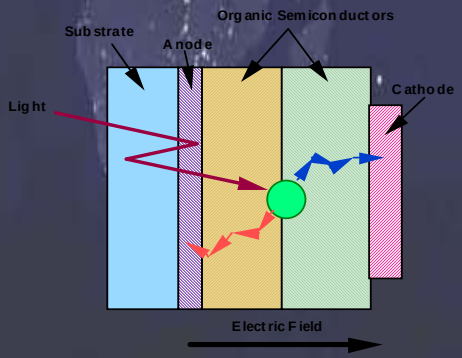
Block Copolymer Morphologies

3. Nanoscale Manipulation

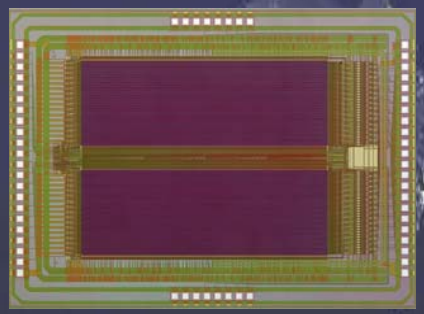
Charge Injection

Tailored Transport & Optical Process

Will Benefit Other Organic Electronics



Organic PVs
Bradley, Imperial College London



1MB prototype chip
shown by Motorola in June 2002

Proposals

- Three to Four Years Duration
- Typically up to one month summer support for the PI, one to two graduate students or a postdoc.
- Success rates on the division level was ~20% in FY 2005.
- Major problem with proposals is that the applicant does not adequately address our ***EMPHASIS ON FUNDAMENTAL SCIENTIFIC RESEARCH.***
- General call for proposals issued near to October 1st of each year and closes September 30th.
- Typically best times to submit proposals are summer through mid-autumn.

Proposals

Web Sites

Information on grant application procedures:
http://www.sc.doe.gov/grants/grants.html

Program web site:
http://www.sc.doe.gov/bes/bes.html
http://www.sc.doe.gov/bes/brochures/CRA.html

Contact information: 301-903-3427

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Concluding Remarks