Cross-cutting Basic Research Needs for Solid-State Lighting from the DOE BES Workshop

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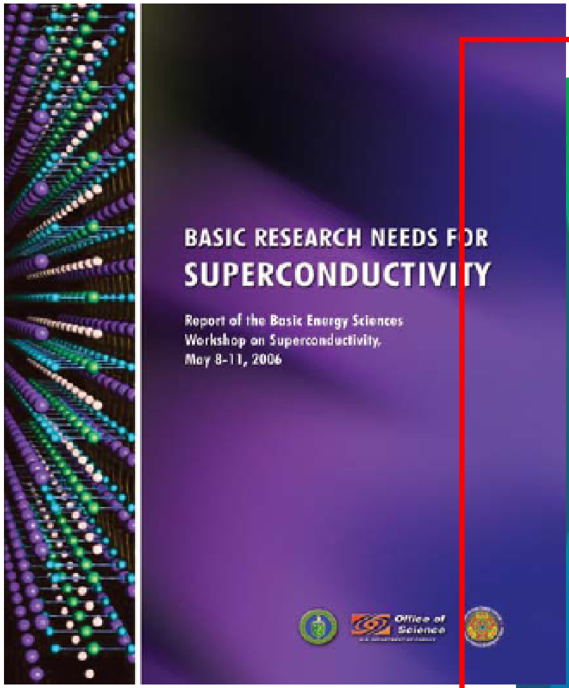
BES Basic Research Needs Workshops

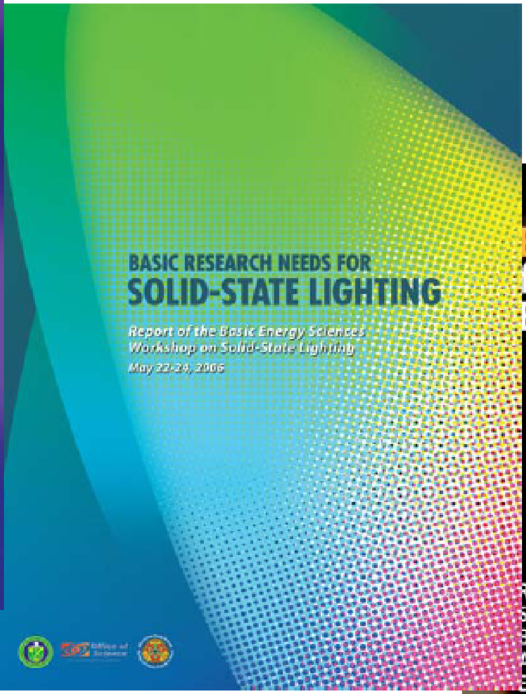
http://www.sc.doe.gov/bes/reports/list.html



BASIC RESEARCH NEEDS FOR
SUPERCONDUCTIVITY

Report of the Basic Energy Sciences
Workshop on Superconductivity,
May 8-11, 2006

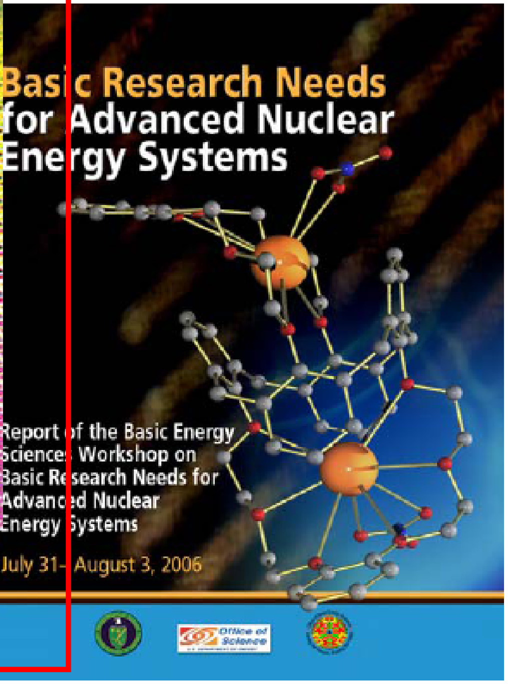
May 2006



BASIC RESEARCH NEEDS FOR
SOLID-STATE LIGHTING

Report of the Basic Energy Sciences
Workshop on Solid-State Lighting
May 22-24, 2006

May 2006



Basic Research Needs
for Advanced Nuclear
Energy Systems

Report of the Basic Energy
Sciences Workshop on
Basic Research Needs for
Advanced Nuclear
Energy Systems

July 31- August 3, 2006

August 2006

http://www.sc.doe.gov/bes/reports/abstracts.html

Workshop on Basic Research Needs for SSL

Chair: Julia Phillips, Sandia National Lab
Co-Chair: Paul Burrows, Pacific Northwest National Lab

Panel 1:

LEDs

Robert Davis
(CMU)
Jerry Simmons
(Sandia)

Panel 2:

OLEDs

George Malliaras
(Cornell)
Franky So
(U. Florida)

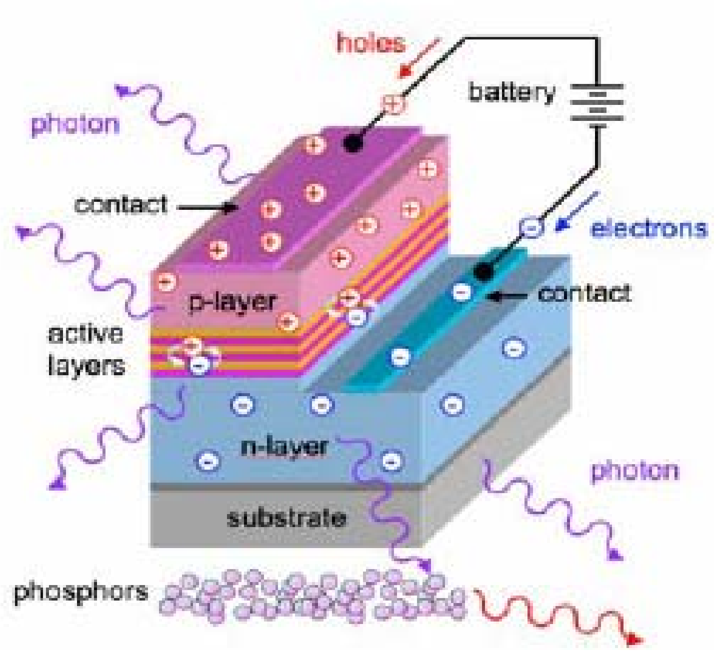
Panel 3:

Cross-cutting Science, Novel Methods

Jim Misewich
(BNL)
Arto Nurmikko
(Brown)
Darryl Smith
(LANL)

Efficiency

Heating: 70%
Electric motors: 85-95%
Lamps: much less !



1.5 Billion light bulbs sold/year (US)
Incandescent lamp (19th century): 5%
Fluorescent lamp (20th century): 20%

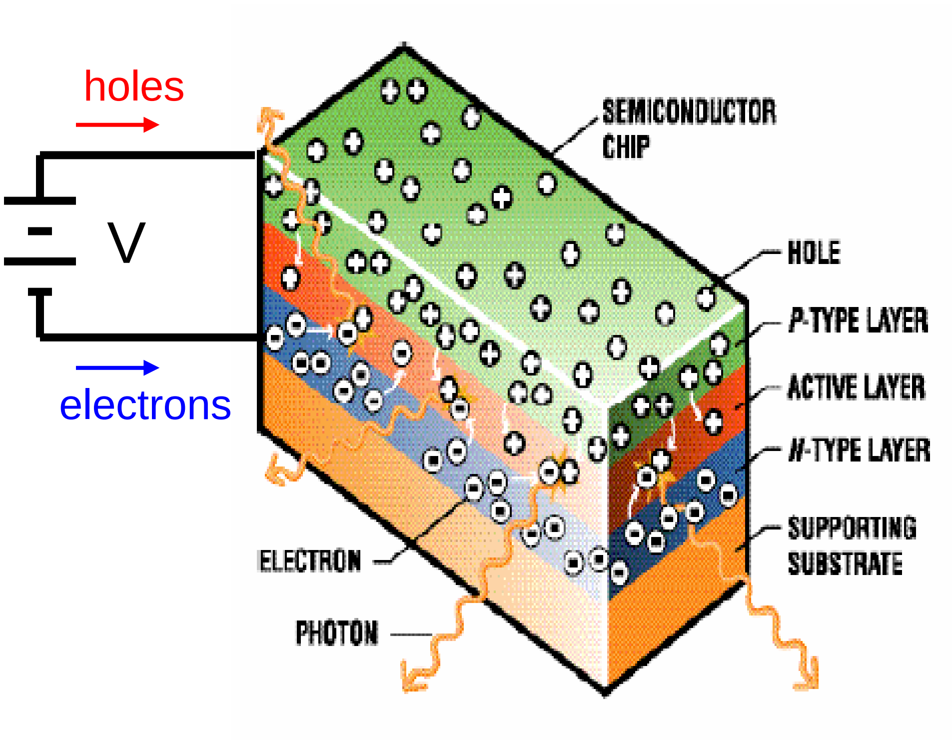
Solid-state lighting (SSL): the direct conversion of electricity to white light using semiconducting materials

21st century opportunities/needs → efficiency

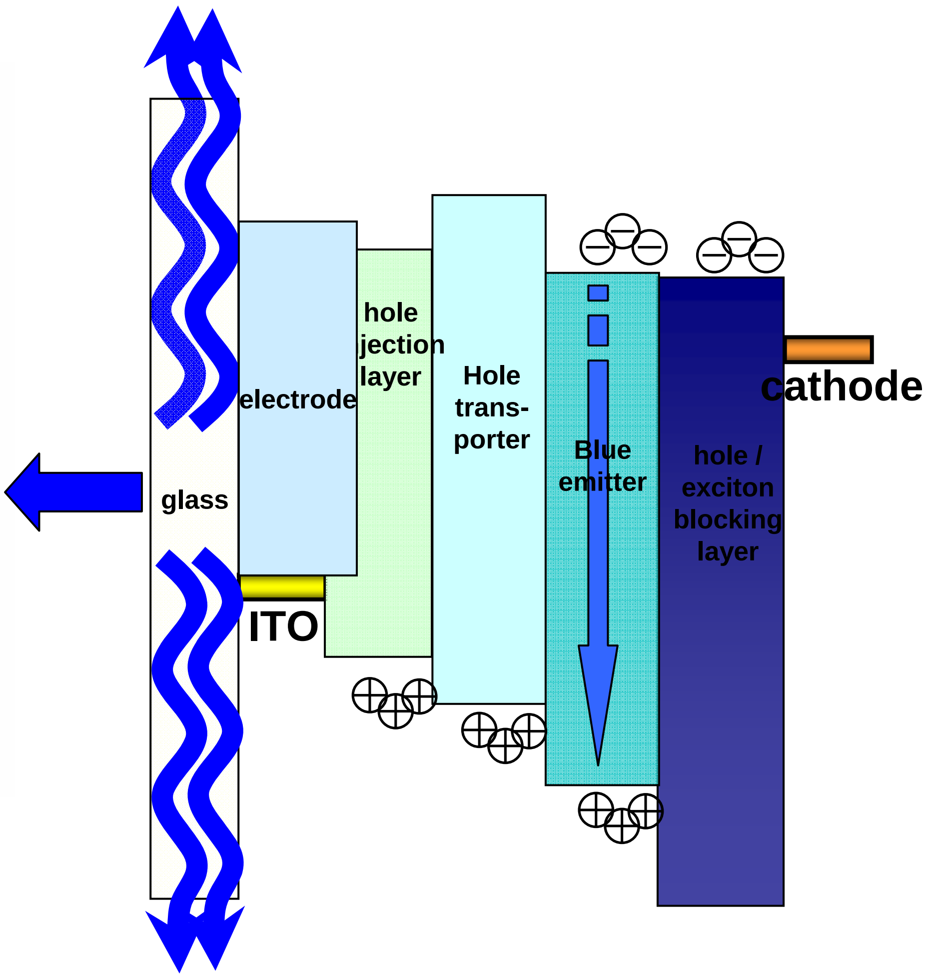
Must have acceptable: Color quality, brightness, cost

Solid state lighting approaches

- LEDs

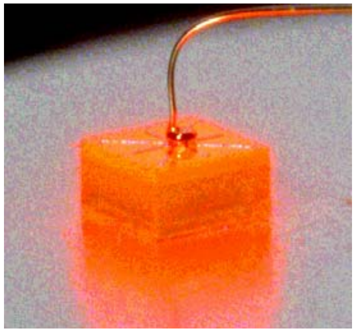


- OLEDs



Inefficiencies Accumulate

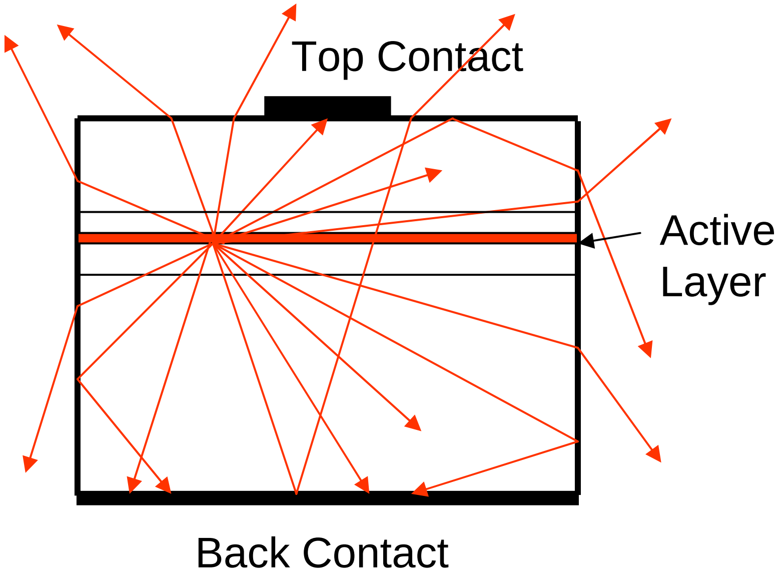
- ***Wall Plug Efficiency (E_{WP})*** -- fraction of energy provided by power source that is converted to **emitted light energy**
- ***Injection Efficiency (E_{inj})*** -- efficiency with which electrons & holes are injected into the active region
- ***Internal Quantum Efficiency (η_{int})*** -- fraction of injected e-h pairs that become photons ***emitted inside*** the die
- ***Light Extraction Efficiency (C_{ext})*** -- fraction of internally emitted photons that escape from the die



$$E_{WP} = E_{inj}\ \eta_{int}\ C_{ext}$$

<u>Other losses (for white SSL luminaire):</u>

- Absorption by contacts, phosphors, encapsulants, etc.
- Phosphor Stokes shift
- Optical element losses



Panel 3: Cross-Cutting Science

- Chairs:
  - Jim Misewich (BNL)
  - Arto Nurmikko (Brown U)
  - Darryl Smith (LANL)
- Panelists:
  - Marc Achermann (U. Massachusetts at Amherst)
  - Vladimir Agranovich (Russian Academy of Science)
  - Len Buckley (NRL)
  - Vladimir Bulovic (MIT)
  - Francois Leonard (SNL)
  - Tony Levi (USC)
  - Shawn Lin (RPI)
  - Lukas Novotny (U Rochester)
  - Peter Littlewood (U of Cambridge)
  - Garry Rumbles (NREL)
  - Peidong Yang (UC Berkeley)
  - Rashid Zia (Brown U)

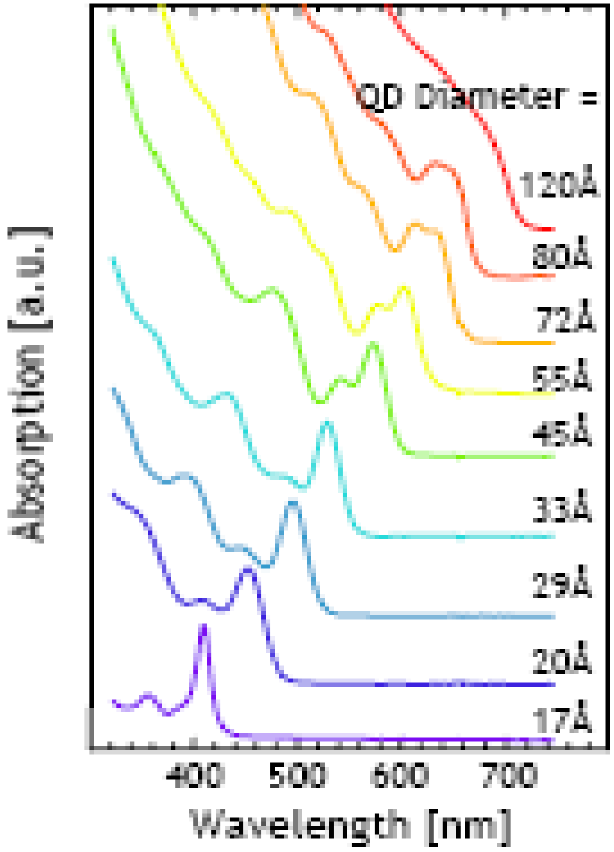
Identify priority research directions and grand challenges

Five Priority Research Directions Identified

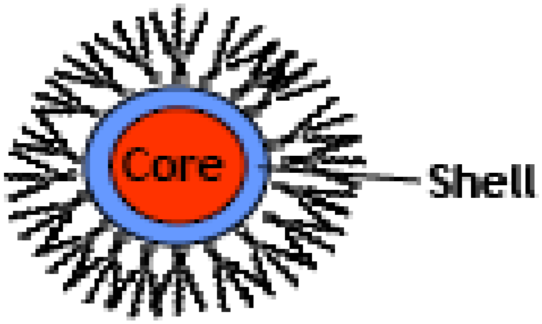
- New functionality through heterogeneous nanostructures
- Innovative photon management
- Enhanced light-matter interaction
- Multiscale modelling for solid-state lighting
- Precision nanoscale characterization for SSL

Nanoscale Materials

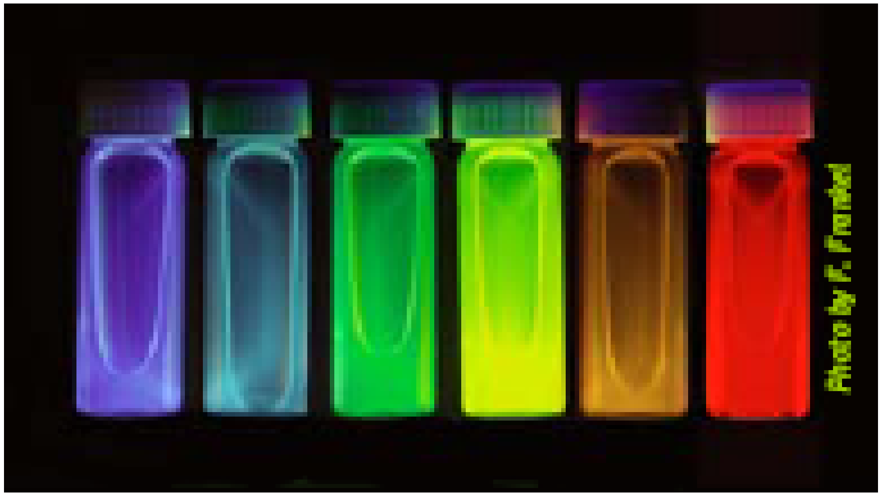
- Tunability: quantum confinement



Absorption Spectra of CdSe QDs

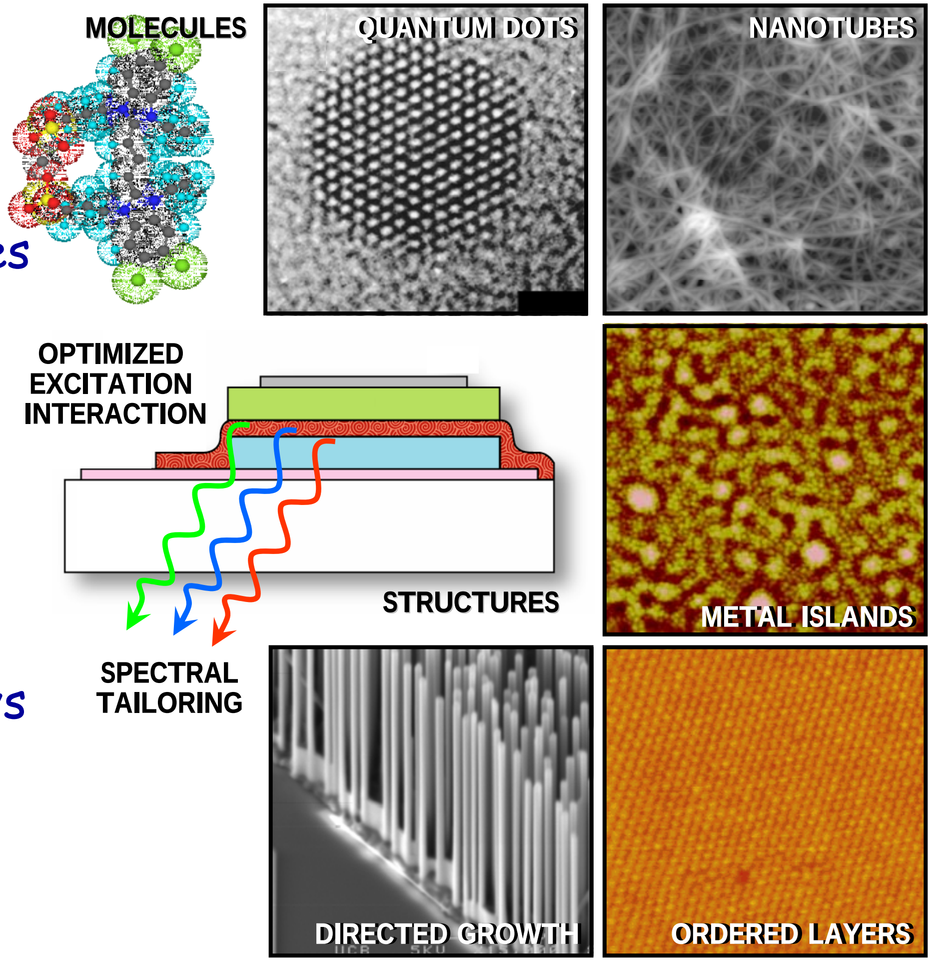


Luminescence of CdSe QDs



New Functionality Through Heterogeneous Nanostructures

- Overview
  - Exploit new degrees of freedom in heterogeneous nanostructures to control fundamental physical processes important for SSL
  - Develop new synthesis and assembly approaches for high quality nanostructured materials and heterostructures
  - Explore the physics and chemistry of macroscopic area nanostructure arrays
  - Integration of nanostructured materials in macroscopic SSL devices



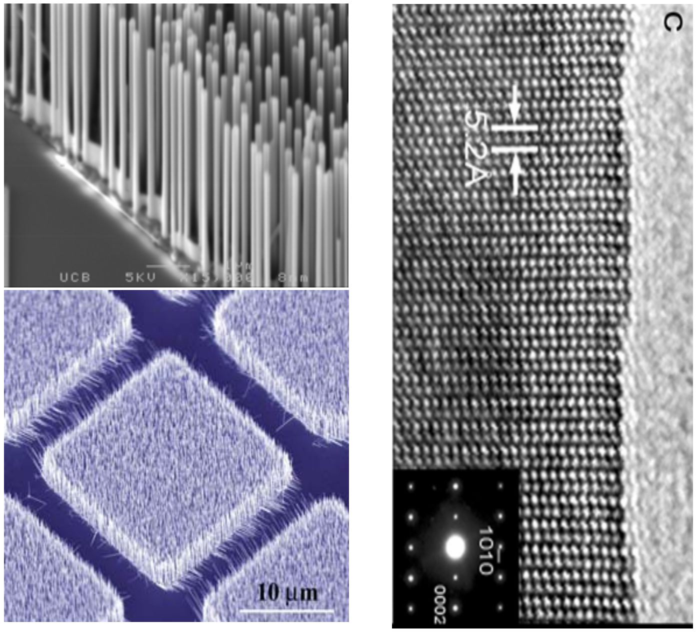
- Impact with success
  - High efficiency and color quality in solid state lighting through increased control of functionality at the nanoscale

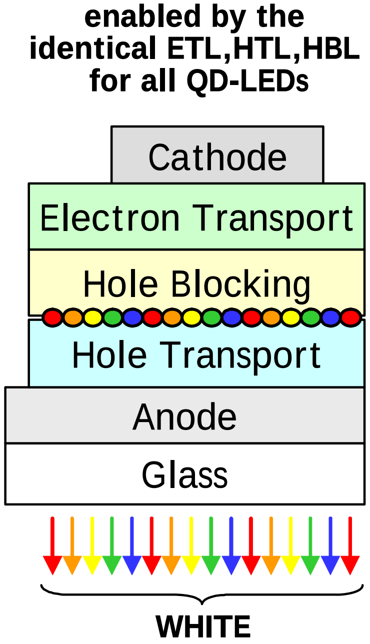
New Functionality
Through Heterogeneous Nanostructures

- Science questions and opportunities
  - Synthesis and Self-Assembly issues
    - Size, composition, passivation and shape controlled synthesis of nanomaterials
    - Environmentally acceptable nanomaterials (sustainable resources, scalable processes)
    - Self-Assembly of nano-elements (organic, inorganic) into enhanced functional forms
  - Understanding and Control of Radiative and Non-Radiative Processes
    - What governs quantum efficiencies at the nanoscale?
    - Manipulating and metering photons, excitons, polarons, phonons, and plasmons in nanostructures
    - Coupled excitations in nanostructures (electron-photon, electron-phonon, …)
    - Optical mode tailoring (directionality of emission, spectral tuning)
  - Integration into SSL Structures
    - Influence of nanostructures on the SSL device designs
    - Array behavior of nanostructures (coupling, cross-talk, periodicity)
    - Opportunities for thermal / mechanical management
    - Enhanced operational stability
    - Nanoscale materials in photonic structures

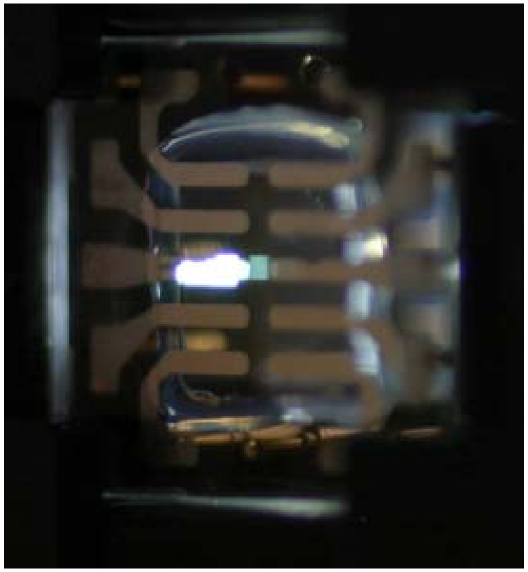
New Functionality Through Heterogeneous Nanostructures

- Recent advances illustrating promise of PRD
  - Yang: dislocation-free nanowires
  - Bulovic: organic/inorganic (QD) hybrid materials



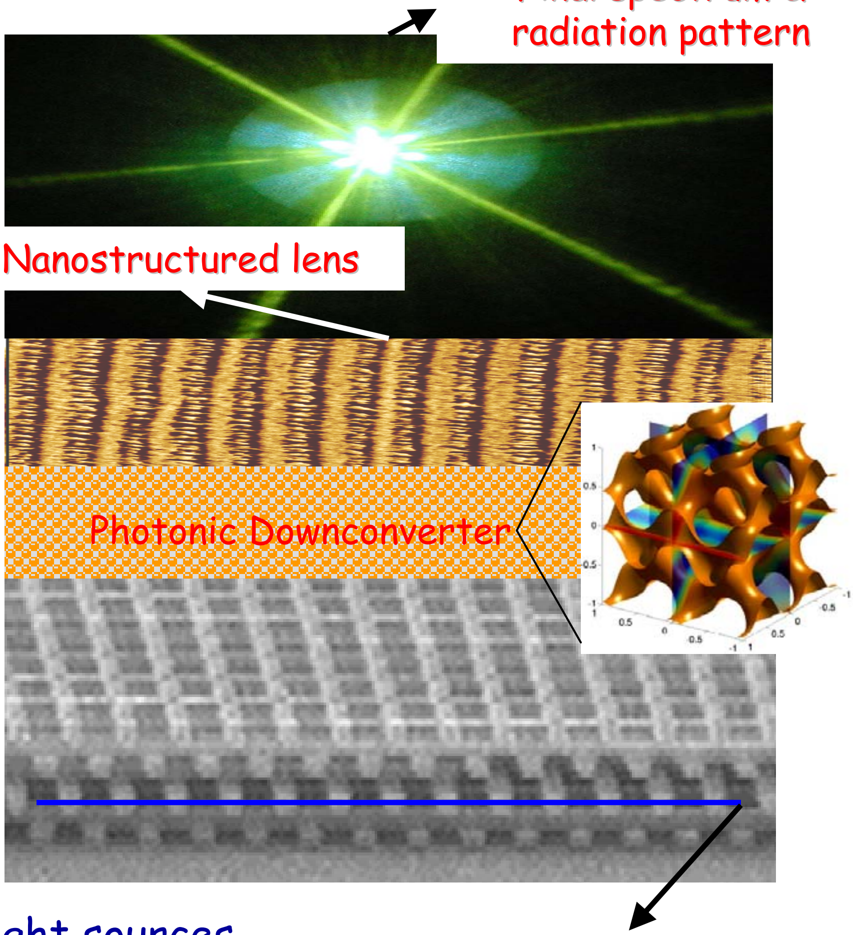


enabled by the identical ETL,HTL,HBL for all QD-LEDs



Innovative Photon Management

- Overview
  - Embedded emitter photonic nanostructures
  - Control over final spectrum, polarization, and radiation pattern
  - Bio-inspired optics and biomimetic approaches
  - Tailoring the density of optical modes



Final spectrum & radiation pattern

Nanostructured lens

Photonic Downconverter

Embedded & enhanced emitter

- **Impact with success**
  - Ultra-efficient, compact, high power light sources
  - Paradigm shift in LED luminaire architectures

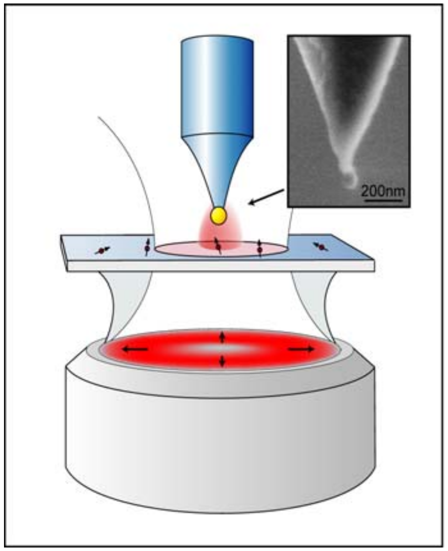
Innovative Photon Management

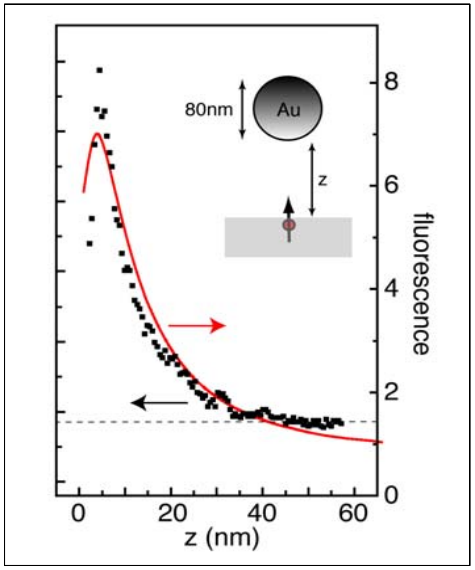
- Science questions and opportunities
  - Ultra-high energy transfer into extracted light spectrum
  - Spontaneous emission and thermal emission modification
  - New luminaire concepts based on large-area nano-structured materials
  - Photonic coupling to desirable down-conversion media
  - Emitters with integrated lens capabilities
  - Bio-inspired optics for large area illumination

- Potential research approaches
  - Facile 3-D nanostructure fabrication techniques
  - Full 3-D Maxwell solvers including photonics/plasmonics for efficient photon mgmt.
  - Novel photothermally stable optical packaging materials

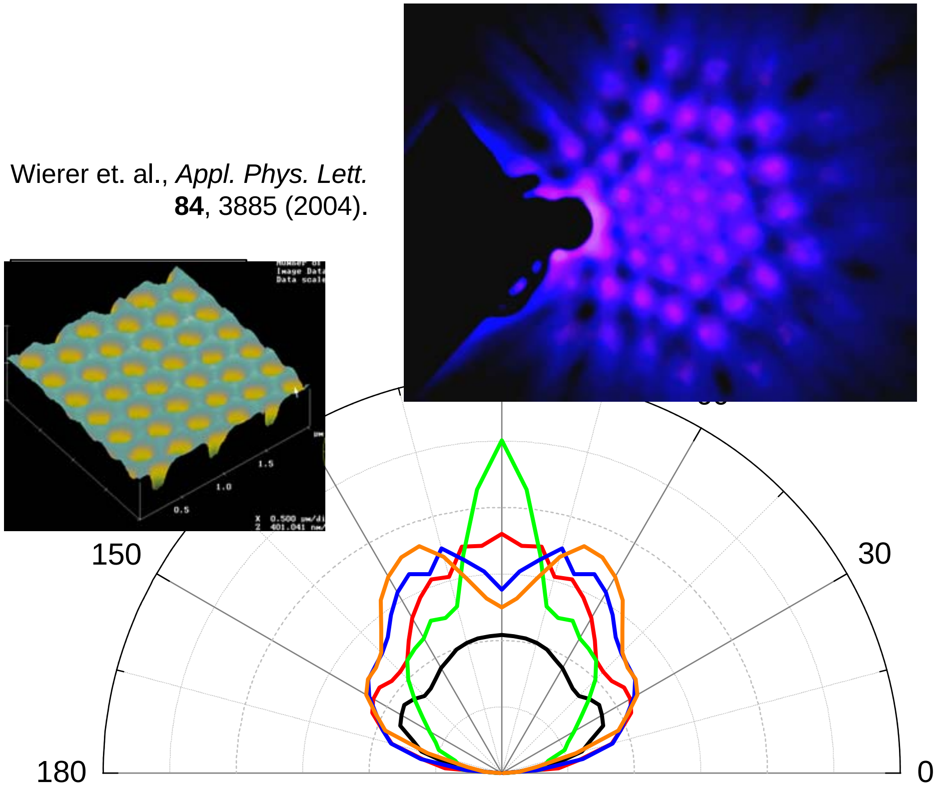
Innovative Photon Management

- Recent advances illustrating promise of PRD
  - Enhanced radiative emission through DOS engineering
  - Photonic nanostructure radiation pattern control





PRL **96**, 113002 (2006)

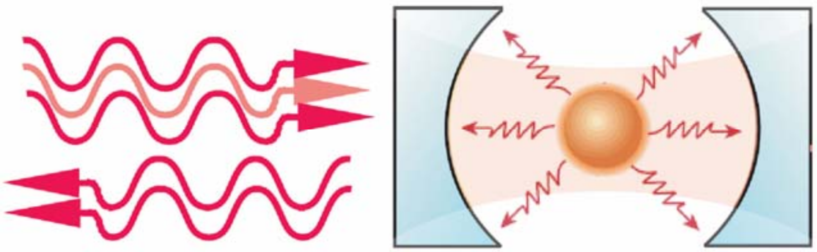


Wierer et. al., *Appl. Phys. Lett.* **84**, 3885 (2004).

Enhanced light-matter interactions

Exploit new degrees of freedom
(enabled by strong coupling)

- Novel control of photon-exciton hybridization
- Enhanced quantum efficiency by resonant light-matter interaction
- Manipulation of collective radiative effects in dense 'multifluorophore' nanoparticle arrays



Control of electron-photon interaction

Impact with success:

leading to dramatic advances and innovations in nanomaterial configurations for high efficiency LEDs

Enhanced light-matter interactions

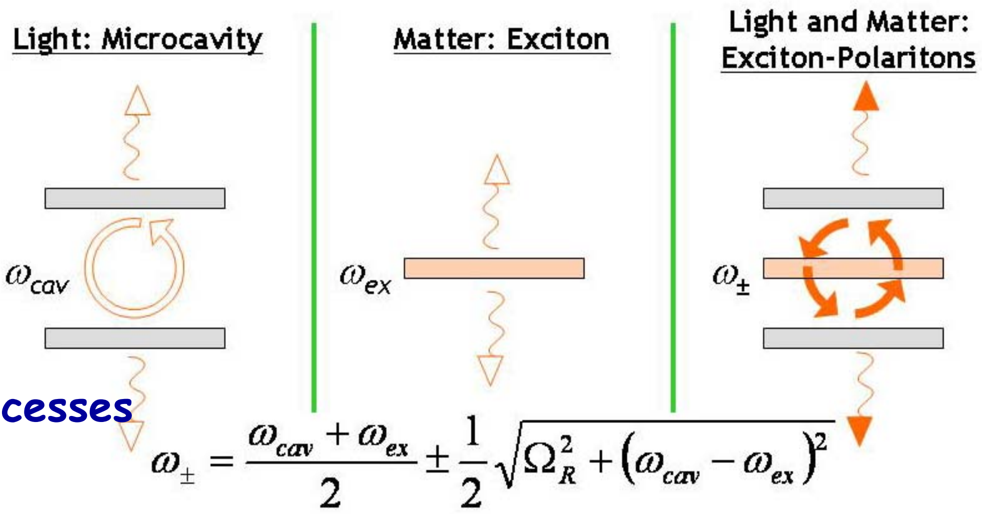
- Science questions and opportunities (research needs)

Integrated photon generation/extraction
New approaches to high performance

- Organic/inorganic hybrids
- 3D-Microcavity confinement
- Nanoplasmonic enhancement
- Enable giant oscillator strength

Control Energy Pathways

- Near-field induced transitions
- Directed Forster energy pathways
- Incoherent vs. coherent Forster processes
- Collective effects in high density quantum confined arrays



$$\omega_{\pm} = \frac{\omega_{cav} + \omega_{ex}}{2} \pm \frac{1}{2}\sqrt{\Omega_R^2 + (\omega_{cav} - \omega_{ex})^2}$$

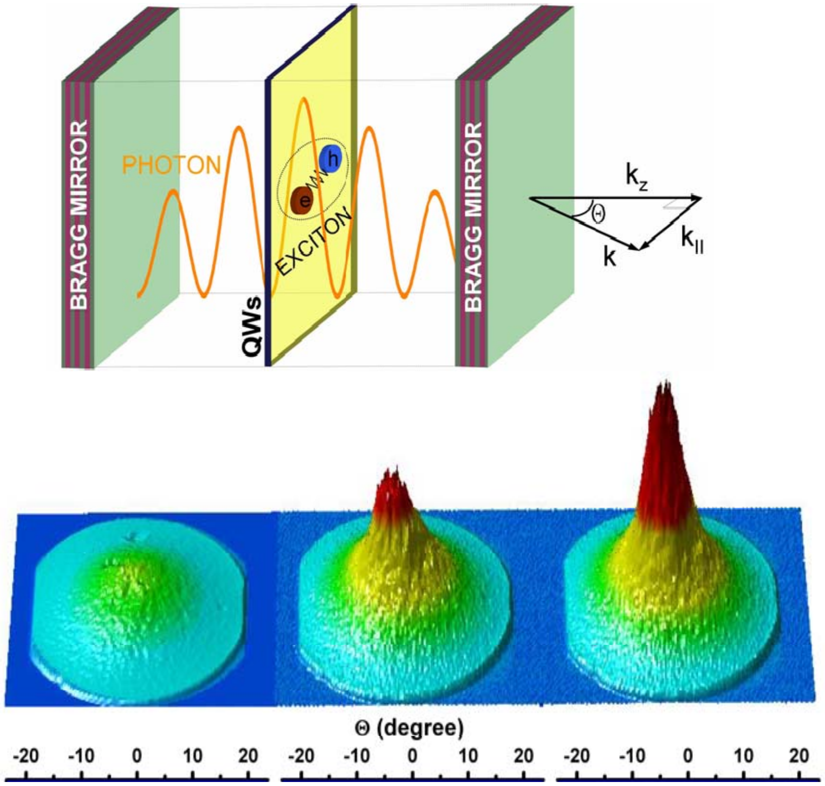
Potential research approaches:

- Chemical synthesis of ordered nanocomposites
- Optimally designed 3D photonic resonators
- Light emitters with quantum-engineered giant oscillator strength
- "smart" spectrally adaptive emitters

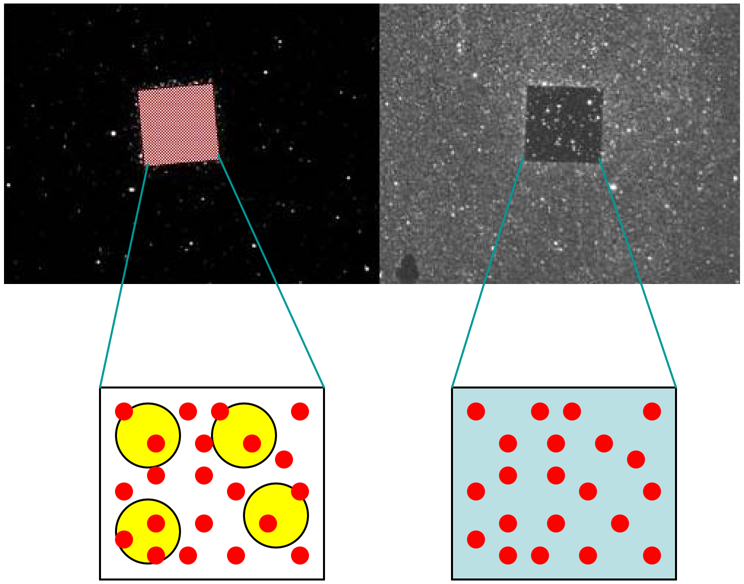
Enhanced light-matter interactions

- Recent advances illustrating promise of PRD

Kasprzak et al (2006)
Coherent Polaritons in
CdTe microcavities (low-T)

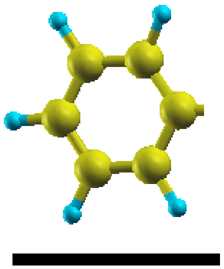


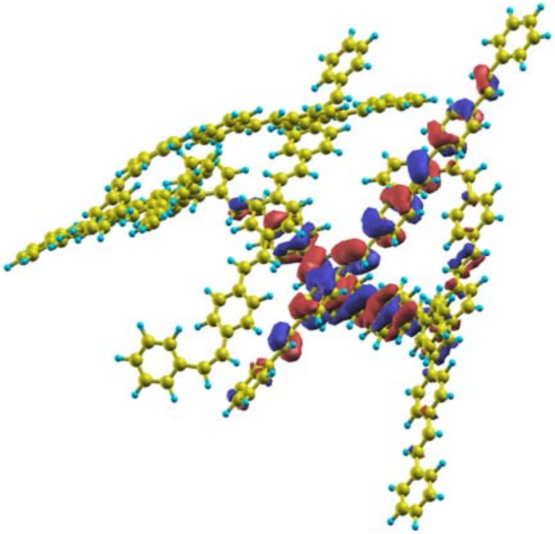
Atay et al (2005)
Fluorescence enhancement
of CdSe/ZnS QD-plasmon
nanoparticle composite



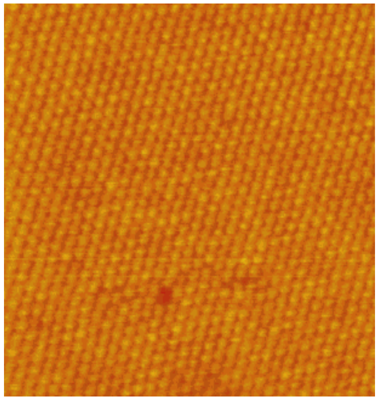
Multiscale modelling for solid state lighting

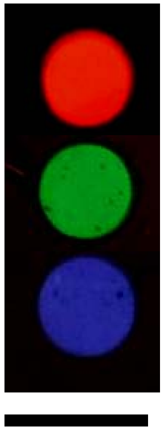
- Overview
  - Hierarchical approach
    - From primary quantum excitations to continuum dynamics
  - Adaptive quantum design
    - Multidimensional optimization
  - Integrated device design
    - Experimental validation





- Impact of success
  - Predictive models enabling full exploitation of opportunities in new materials
  - Rational design for advanced concepts in solid state lighting

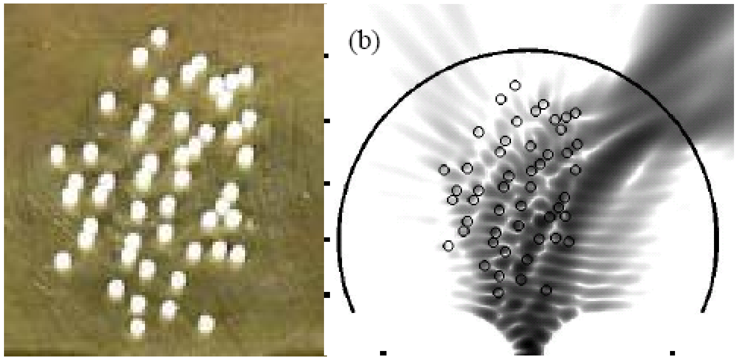




Bulovic *et al* MIT

Multiscale modelling for solid state lighting

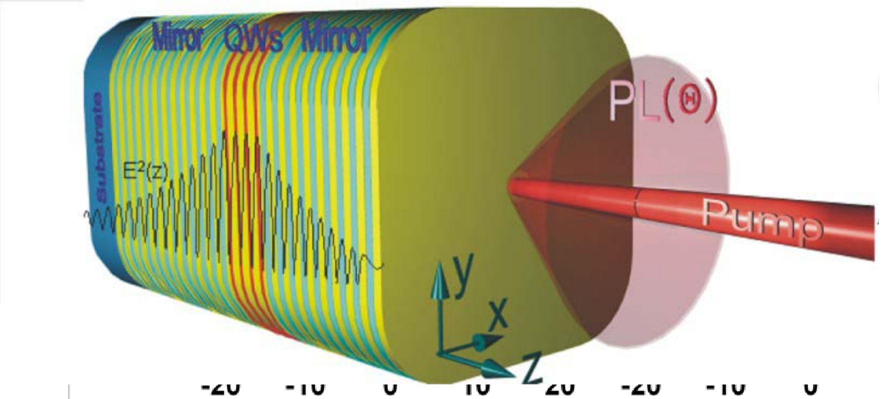
- Science questions and opportunities (research needs)
  - Predictive models for solid state lighting devices
  - Disordered molecular materials
  - Integrated optical and electronic models
  - Ab-initio methods for excited states
  - Kinetics and non-equilibrium phenomena
  - Transport (energy, charge, light and heat)



- Potential research approaches
  - Quantum design from basic principles
    - Discovery of new physical phenomena
  - Hierarchical models
    - Primary quantum excitations (e.g. ab-initio quantum chemistry, density functional theory, quantum Monte Carlo)
    - Large-scale, inhomogeneous model Hamiltonians (e.g. optical modes, hopping transport)
    - Semiclassical dynamics (e.g. coupling to external reservoirs, phonons, kinetics, pumping)
    - Device level models (e.g. rate equations, drift-diffusion)
  - Integrated device design
    - Carrier injection, transport and dynamics
    - Interfaces
    - Experimental validation

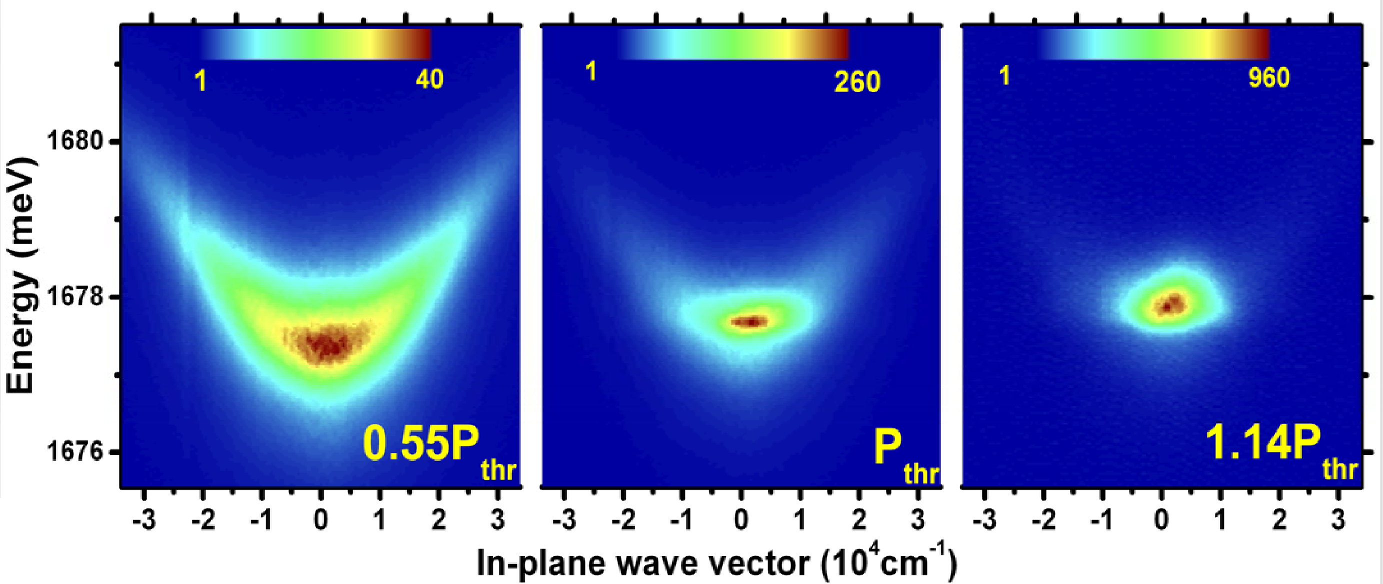
Multiscale modelling for solid state lighting

- Recent advance – quantum coherence in a planar microcavity



Coherent light-matter interaction

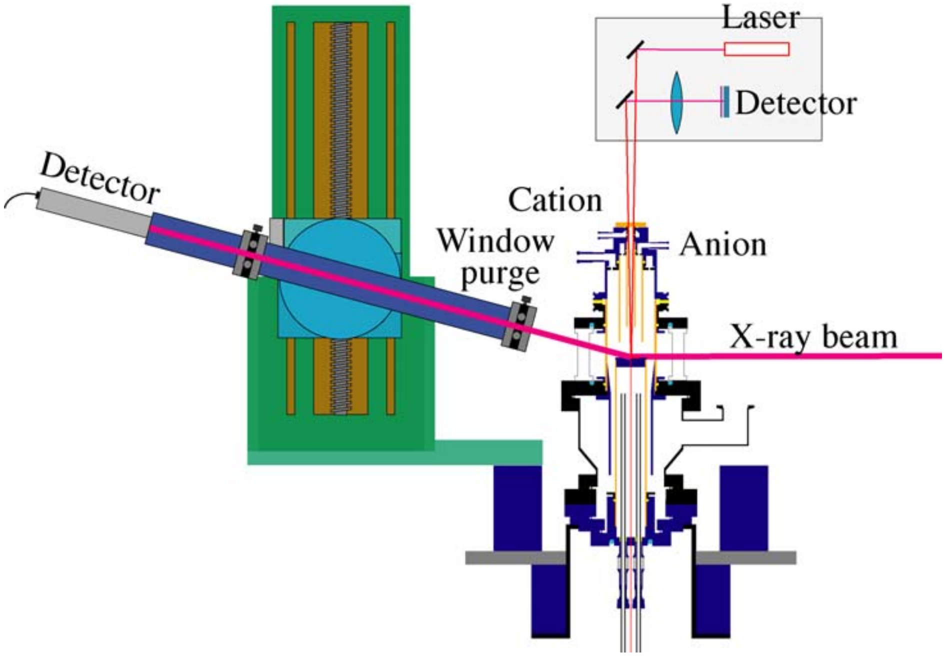
Bose-Einstein condensation of entangled light and matter



Kasprzak et al. (2006)

Precision Nanoscale Characterization for SSL

- Overview
  - Develop new structurally sensitive tools with resolution from molecules to materials.
  - Imaging structure and function in operating SSL devices allowing for the measurement of local (nanoscale) properties



In situ x-ray characterization of MOCVD at the APS

- Impact with success
  - Provide unprecedented feedback and control for improved growth/synthesis.
  - Simultaneous measurements of different physical properties (e.g. optical, structural, and electronic) allowing for evaluating strategies of generation and extraction of photons.

Precision Nanoscale Characterization for SSL

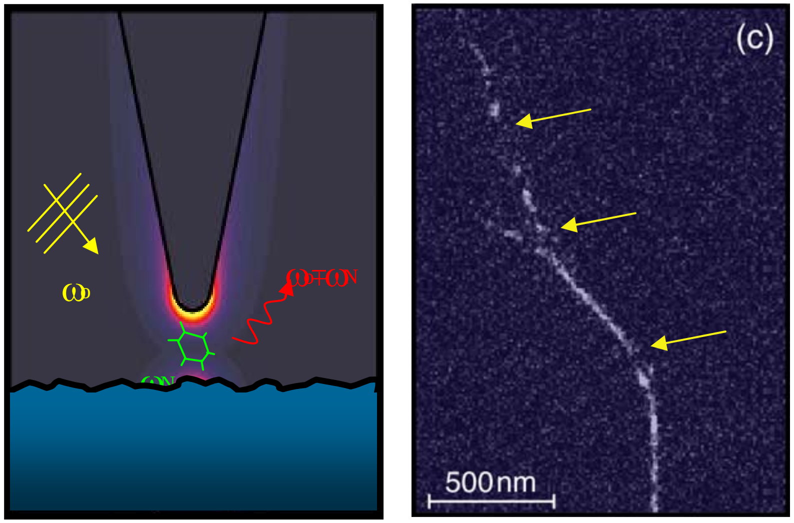
- Science questions and opportunities
  - Simultaneous structure and function
  - Subsurface/buried interface imaging
  - Quantification of Impurities/dopants/defects
  - Unprecedented spatial and temporal resolution

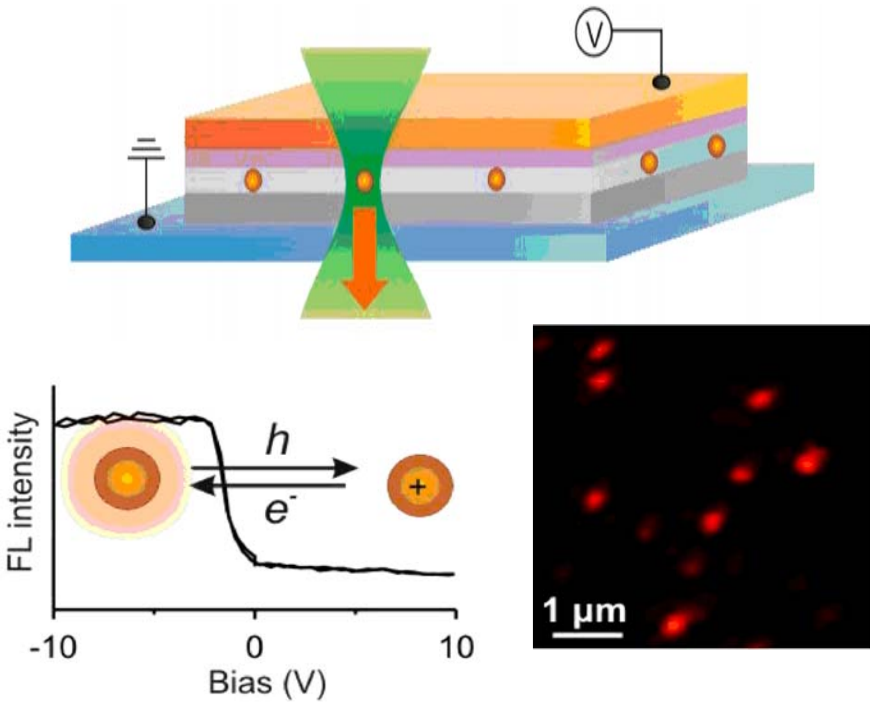
  - Non-invasive
  - Chemically-specific
  - 3d reconstruction
  - Novel combinations

- Potential research approaches
  - Xray techniques including in situ microscopy, ultrafast time resolved scattering and spectroscopies, and inelastic scattering.
  - Single molecule (particle) optical techniques using new interaction mechanisms (nonlinear optical, Raman, ..).
  - Nanoscale chemically-specific imaging with scanning probes including near-field optical spectroscopy (IR, Raman).
  - Advanced imaging tools for spin degrees of freedom.
  - Electron and ion beam techniques with enhanced energy and spatial resolution for improved sensitivities to avoid sample damage.

Precision Nanoscale Characterization for SSL

- Recent advances illustrating promise of PRD
  - Novotny: Near-field Raman spectroscopy
  - Barbara: Single molecule spectroscopy in a functioning device



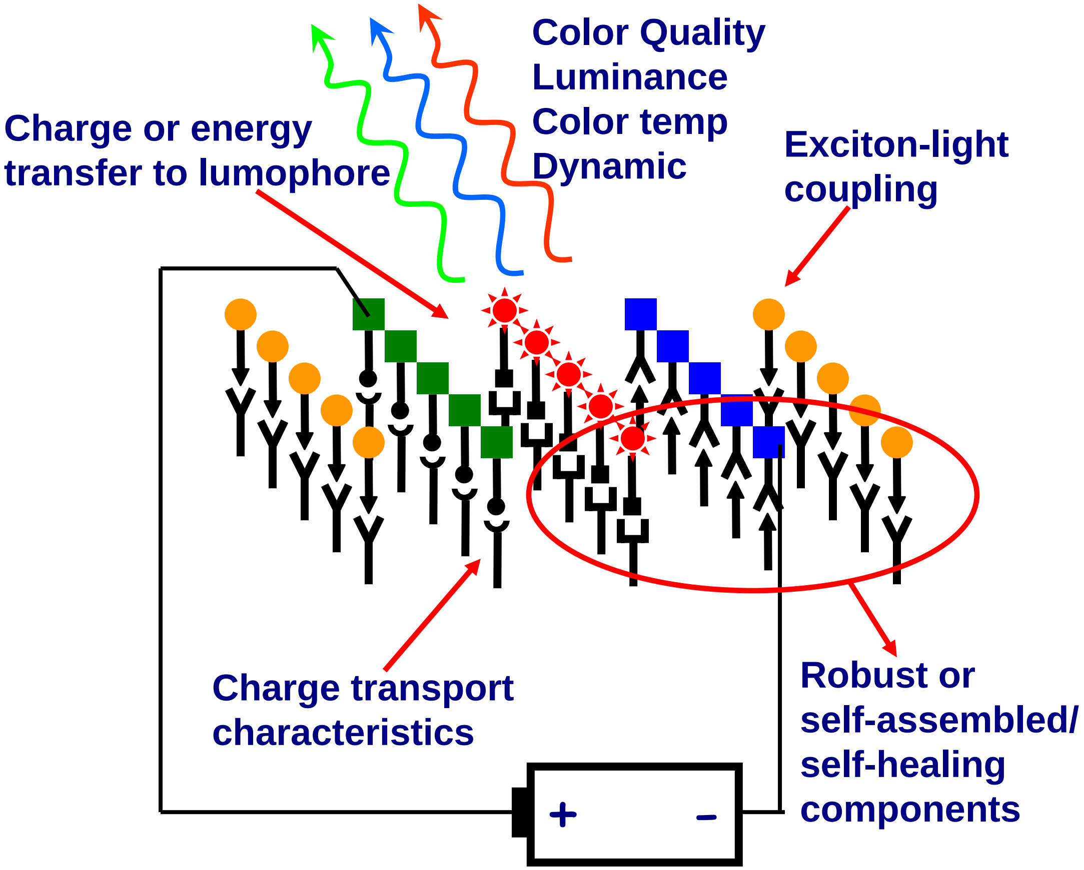


Grand Challenge

- Rational design of solid-state lighting systems

Rational design of solid-state lighting systems

- Control for ultimate efficiency through:
  - Designed optical properties
    - Emission spectrum
    - Radiative rate
    - Minimized parasitic processes
  - Designed transport properties
    - High mobility
    - Optimized contacts
  - Multidimensional optimization



Color Quality
Luminance
Color temp
Dynamic

Charge or energy transfer to lumophore

Exciton-light coupling

Charge transport characteristics

Robust or self-assembled/ self-healing components

Rational design of solid-state lighting systems

- Fundamental materials science needs
  - Physics: ability to precisely tune basic physical properties
    - New functionality through heterogeneous nanostructures
    - Enhanced light-matter interaction
    - Innovative photon management
    - Discovery of design rules for robust photon conversion materials & matrices for use in the UV-Vis-IR
  - Chemistry: high-quality materials, high precision placement
    - Computational design and/or synthesis of unconventional light emitting materials with tailored properties
    - Manage & exploit disorder in OLEDs
    - Understand the origins of OLED degradation
  - Theoretical understanding
    - Multiscale modelling for solid-state lighting
    - Understand & control highly polarized materials & heterojunctions
    - Integrated approach to OLED design