SOLID-STATE LIGHTING

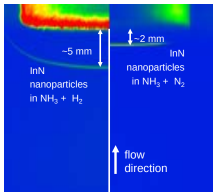
Semiconductor-based white light for ultra-efficient illumination

EXPLORE AND COLLABORATE
AMERICAN INDUSTRY AND AMERICA'S NATIONAL LABS
MATERIALS FOR ENERGY APPLICATIONS

Semiconductor-based solid-state lighting (SSL) has become as efficient as incandescent (4%) and fluorescent (20%) lighting. In the long run, energy conversion efficiencies exceeding 70% are believed achievable. Challenges to be addressed include the materials (organics, InGaN, AlInGaP, phosphors, II-VI's) and architectural building blocks (planar films, nanowires, nanodots) that comprise current and future solid-state lighting.

Light Emitting Materials

Indium Gallium Nitride (InGaN) and, to a lesser extent Aluminum Indium Gallium Phosphide (AlInGaP) materials are the backbone of solid state lighting, providing the materials on which inorganic blue and red LEDs are based. However, these materials are difficult to synthesize, particularly at compositions which would enable a "filling in" of the visible spectrum into the shallow red, yellow and green. DOE Labs are helping a fundamental understanding of the synthesis of both InGaN (SNL, ANL) and AlInGaP (NREL) materials.

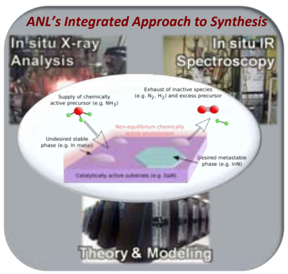


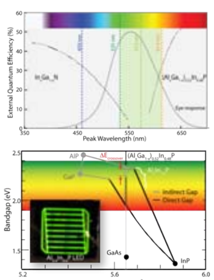
InGaN: Process Monitors and Reactive Fluid Flow Models for Improved MOCVD Tools and Manufacturing (SNL)

Veeco, in collaboration with Sandia, has been developing comprehensive computational reactive fluid flow models for InGaN deposition to increase yield and reduce manufacturing cost. The models make use of novel measurements, such as shown here, of parasitic nanoparticle formation which form routinely during synthesis. New pyrometry tools for temperature measurement have also been developed.

InGaN: Reactive Synthesis of Metastable Materials (ANL)

By varying the composition of $In_xGa_{1-x}N$, its bandgap can be tuned across the entire visible and solar spectrum, making it very attractive for solid-state lighting. However, recent studies have shown that high nitrogen activity is needed to stabilize high-In-content $In_xGa_{1-x}N$ during growth. We are utilizing *in-situ* grazing incidence surface x-ray diffraction, *in-situ* IR spectroscopy, and multiscale theory and simulation to understand how intermediate chemical species resulting from the decomposition of NH_3 might enable such non-equilibrium synthesis.





AlInGaP (NREL)

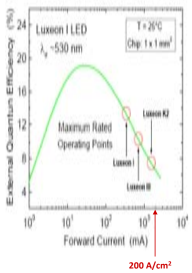
Solid state lamps based on RYGB architectures are among the most promising approaches for high efficiency lighting. The blue and red LED components can be fabricated with relatively high efficiencies, yet those of green and yellow LEDs currently suffer from fundamental material limitations. Our work explores $Al_xIn_{1-x}P$, a material with the highest direct-indirect crossover energy of the non-nitride III-V alloys and ipromising for LEDs at yellow-green wavelengths. Difficulties with metamorphic growth on GaAs substrates and O-contamination have until now limited the use of $Al_xIn_{1-x}P$ for the light-emitting layer of visible LEDs. Our ability to control both makes $Al_xIn_{1-x}P$ accessible for solid state lighting applications.

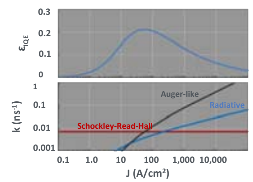
Light-Emission Physics and Architectures

Conventional light-emitting diodes rely on spontaneous emission mediated by electron-hole-pair recombination in planar 2D architectures. However, the microscopic processes associated with such recombination (and competing non-radiative routes) are poorly understood, particularly in InGaN materials. DOE Labs are helping build a fundamental understanding of these processes (SNL, LBNL). And, in parallel, DOE Labs are exploring alternative light-emission architectures (e.g., lasers and stimulated emission (SNL), 1D nanowires (LBNL, SNL), and 0D nanocrystals (LANL)), as a means to improve light-emission efficiency across the visible spectrum.

Competing Radiative and Non-Radiative Processes (SNL)

DOE labs are helping develop a microscopic understanding of the competing physical processes that determine light-emission efficiency of InGaN materials and heterostructures. Of particular interest is the so-called "droop problem," in which efficiency rolls off at high currents. The origin of droop is not yet known, and is the topic of intense current research.



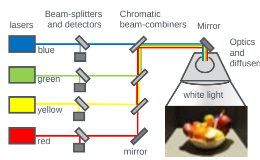


$$\varepsilon_{IQE} = \frac{Bn^2}{An + Bn^2 + Cn^3 + Dn^m + \ldots}$$

Shockley-Read-Hall (non-radiative at defects) — Radiative — Auger and higher-order processes

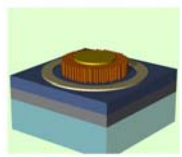
Stimulated Emission (SNL)

One potential way of circumventing efficiency droop is the use of stimulated emission. However, lasers are narrow-linewidth sources, and it is not obvious that they can create high-color-rendering-quality white light. DOE labs have now demonstated that a four-color laser illuminant does indeed have color-rendering quality comparable to incandescent and other LED sources, according to human subjects testing.

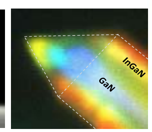


InGaN Nanowire Based LEDs (LBL, SNL)

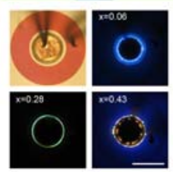
InGaN nanowires have many potential advantages as a materials architecture for visible light-emission: the potential for high-quality material without detrimental line defects; the ability to accommodate lattice strain and therefore a wider range of alloy compositions and bandgaps; and manipulability of growth geometries so as to expose surface orientations with tailored light emission properties. DOE Labs are helping develop this emerging materials architecture: materials synthesis and processing of both photo- and electro-luminescent structures, and optical, electrical, mechanical and structural characterization.



Nanowire Templated Substrate



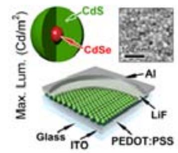
In Composition Map of a Nanowire



Nanowire LEDs

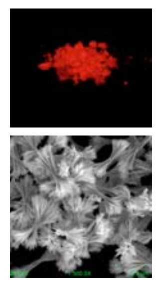
Giant Nanocrystal Quantum Dots as Efficient Electroluminescent Materials (LANL)

- g-NQDs integrated into simple 'test-bed' LED structure
- LED comprising ultra-thick-shell g-NQD (16 monolayers CdS) active layer afforded 0.17% EQE and 2000 Cd/m² luminance
  - ✓ Rivals 'optimized' LEDs based on conventional NQD active layers
  - ✓ ~2 orders-of-magnitude improvement over similar 'simple' LEDs comprising conventional core/shell NQDs
- g-NQD 'solid-state' performance dramatically improved compared to conventional core/shell NQDs due to suppressed Auger recombination, suppressed energy transfer, and enhanced photo-chemical stability
- Thick shell does not impede charge injection (constant EL turn-on voltage)

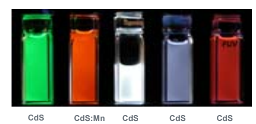


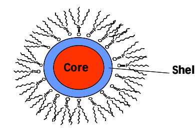
Wavelength Downconversion: Phosphors and QDs (LANL, SNL)

A key component of solid-state lighting technologies involves materials that convert shorter wavelength light to longer wavelengths. Phosphor materials currently used for this purpose have significant emission in the deep red and infrared where the human eye is insensitive, thereby lowering efficiency. To remedy this, DOE laboratories are investigating new Eu^{3+}-based phosphor materials (SNL) as well as novel core-shell quantum dot materials in which optoelectronic properties can be engineered through dot size, core-shell structure, and ligand coverage (LANL, SNL). Both these approaches promise narrow linewidth red emitters.



Rare Earth Tantalate Phophors





Quantum Dot "Phosphors"

Organic SSL

Though inorganic semiconductors dominate the current generation of solid-state lighting, organic semiconductors have some potential advantages, including low-cost and compatibility with large-area lighting geometries. However, organic materials also face a number of challenges, including reliability and actually realizing the manufacturing scale-up necessary for low cost. DOE Labs (PNNL, LBL) are researching both of these challenges.

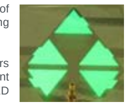
OLED Materials: From Substrates to Packaging (PNNL)

Focused on accelerating the adoption of high-efficiency OLED solid state lighting into the marketplace

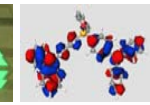
Working with industry partners throughout the supply chain (component developers, suppliers and OLED manufacturers)

Capabilities encompass R&D to scale-up:

- Molecular design and computational chemistry
- Organic electronic materials synthesis, scale up and purification
- OLED fabrication, testing and encapsulation
- State of the art materials characterization
- Thin films deposition process development



OLED on flexible aluminum substrate



Computational design of organic materials

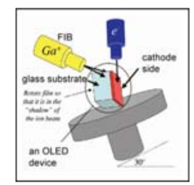
Commercialized moisture barrier technology

High-efficiency blue/white OLED materials

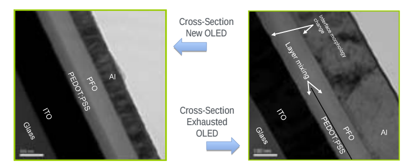
OLED Failure: Focused Ion Beam (FIB) and Transmission Electron Microscopy (TEM) Studies (LBL)

A remaining challenge in OLED materials is increasing their lifetime. By achieving a deeper understanding of how OLED materials age and by what mechanisms they fail, new materials can be created and new device achitectures can be designed, which will be more reliable and have longer lifetimes.

LBL has developed a technique for rapid TEM imaging of OLED devices at the atomic scale. TEM (transmission electron microscopy) typically involves creating thin slices of only a few atomic layers thick, so that the TEM beam can pass through them. This is difficult to do with soft, elastic materials such as polymers. Using a FIB (focused ion beam) in situ within the TEM, LBNL researchers can create narrow slices of material and readily image them at the atomic scale.



An OLED device in the FIB chamber OLED dimension at 1x1x1 mm



Direct observation of OLED interfacial physical degradation

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