Nanoengineering for Solid-State Lighting

Applying nanoscience and nanoengineering concepts to enable energy-efficient LED-based lighting

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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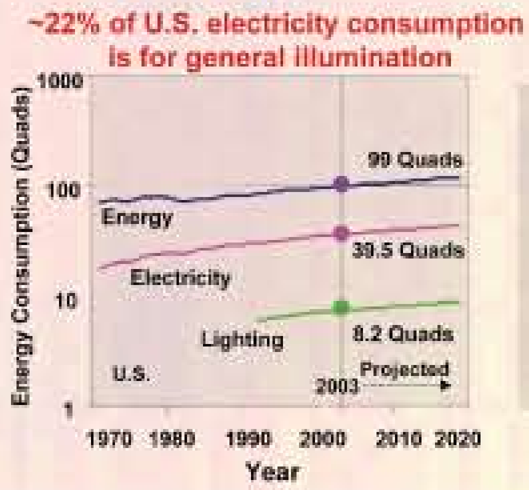
Problem:

Traditional lighting is a large fraction of U.S. energy consumption and has low efficiency

~22% of U.S. electricity consumption is for general illumination



Efficiencies of energy technologies in buildings:	
Heating:	70 – 80%
Electric motors:	85 – 95%
Fluorescents:	20%
Incandescents:	5%

- Lighting is a highly attractive target for reducing energy consumption

Next Generation Solution:

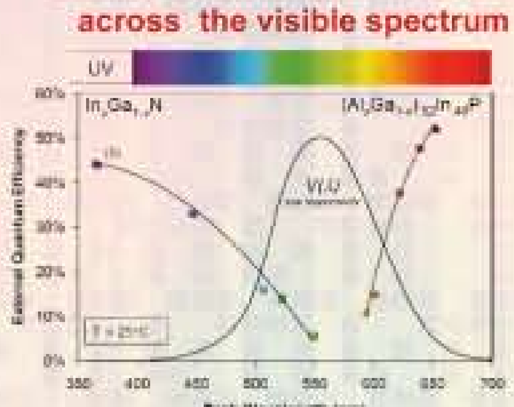
High-efficiency lighting systems based on light-emitting diodes (Solid-State Lighting)

Major technical challenges for LED-based lighting:

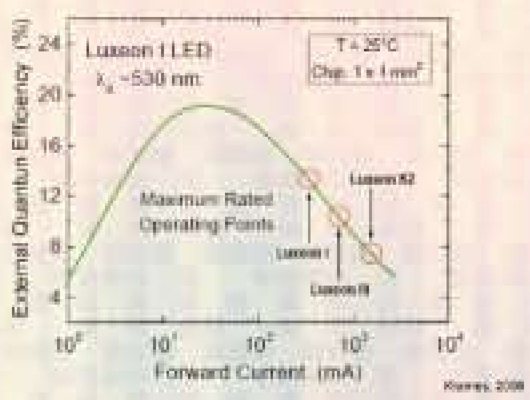
Need high-quality white and high output powers for illumination applications


Courtesy of E F. Schubert

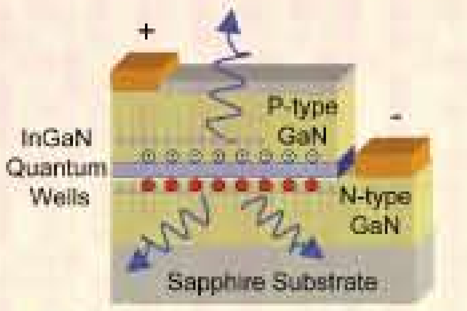
Lack of efficient LED materials across the visible spectrum



LED "Efficiency Droop" at high current densities



Approach:



InGaN Semiconductor LED Structure

Processes leading to LED light emission:

- Conversion of electricity to light inside the LED chip (internal quantum efficiency)
- Extraction of light from the LED chip (extraction efficiency)

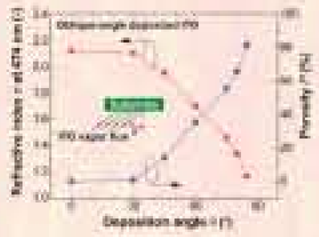
Apply nanoengineering and nanoscience concepts to improve the efficiency of InGaN semiconductor LEDs in two ways:

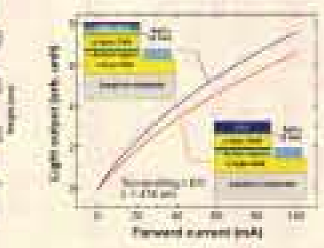
- Study of nanoscale InGaN materials properties to fundamentally improve internal quantum efficiency (focus on nanoscale crystalline defects)
- Nanoscale engineering of dielectric and metal materials and integration with LED structures to enhance light extraction

Results:

Improved light extraction through nanorod coatings

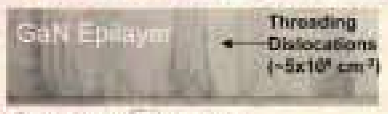
- Developed and applied novel graded refractive index (GRIN) coating materials based on dielectric nanorods





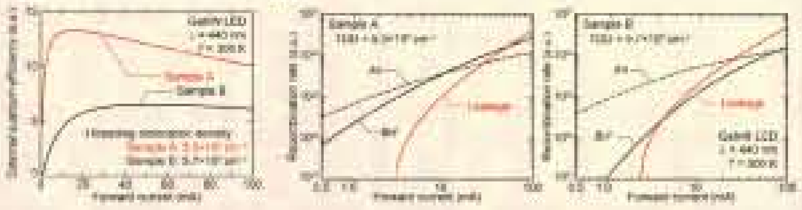
- Realized a 28% increase in LED output power with GRIN ITO coatings

Mechanisms behind InGaN LED "Efficiency Droop"



Do the high densities of extended defects in InGaN LEDs contribute to "efficiency droop" at high currents?

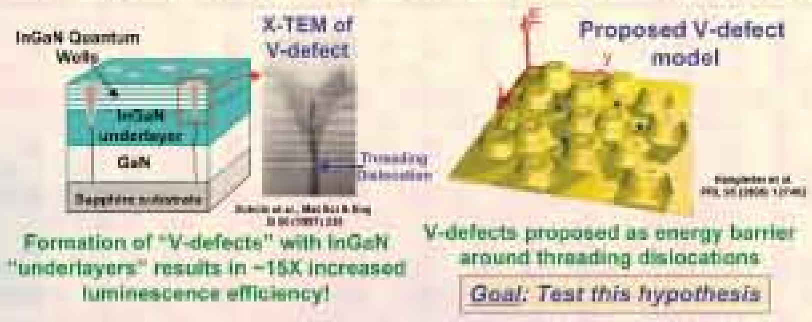
Measurement and modeling of InGaN LEDs with different dislocation densities



- Achieved a range of dislocation densities in InGaN LEDs through controlled nucleation of GaN template layers on sapphire substrates
- LED analysis reveals *similar* recombination rates at high currents for samples with different dislocation densities
- *Proposed high-current mechanism:* carrier leakage out of active region

Impact of Structural Defects on InGaN Luminescence Efficiency

Do "V-defects" prevent non-radiative recombination of carriers at threading dislocations and increase internal quantum efficiency?



Novel approach:	Demonstrated the ability to switch on or off V-defect formation with growth temperature of InGaN underlayer
Observation:	Luminescence enhancement seen for all InGaN quantum well samples on InGaN underlayers---with or without V-defects

- Mechanism for underlayer-induced efficiency enhancement under study

Summary and Significance:

Joint Sandia and Rensselaer Polytechnic Institute LDRD effort

- Demonstrated the potential for LED efficiency improvements across the spectrum with the implementation of nanorod-based GRIN coatings
- Achieved insight into the fundamental mechanisms behind LED "efficiency droop" at currents needed for illumination applications
- Clarified the impact of nanoscale crystalline defects on the luminescence efficiency of InGaN LED structures

Potential for high impact: if 2025 Solid-State Lighting 50% efficiency goals are met, U.S. electricity consumption will be reduced by 10% (50% reduction of electricity for lighting), saving > $25B/ year, and reducing carbon-equivalent emissions by about 100 Megatons/year

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