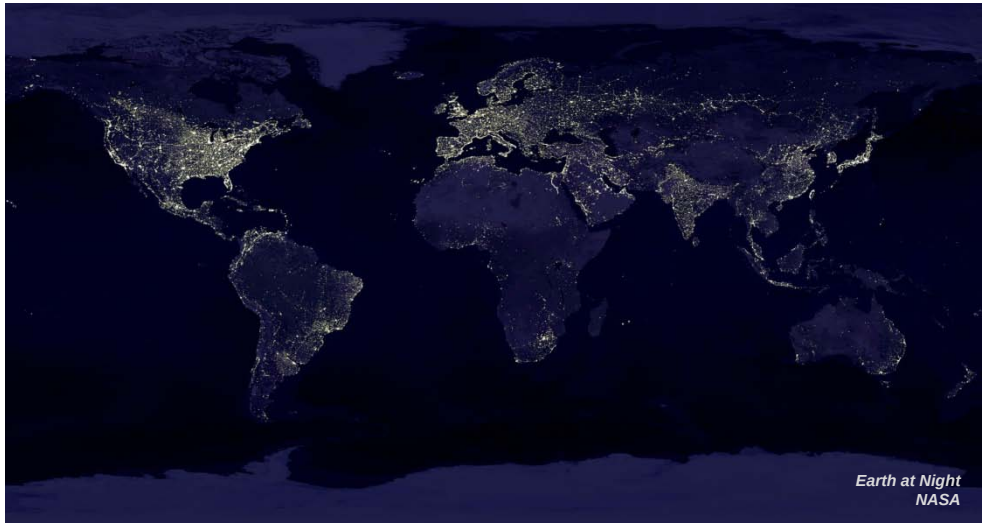
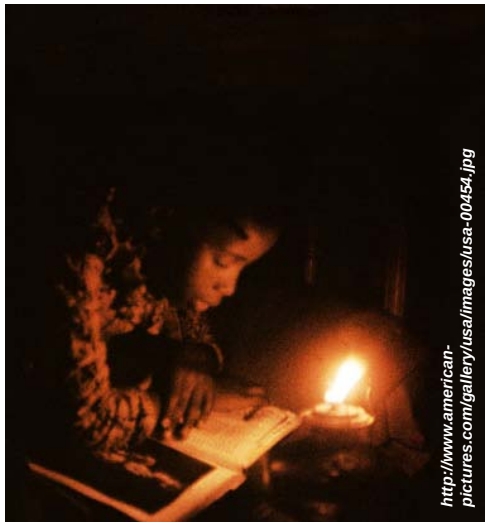
Sandia's Energy Frontier Research Center (EFRC) for Solid-State Lighting Science

Management: *Jerry Simmons (Director), Mike Coltrin (Co-Director), Jeff Tsao (Chief Scientist)*
Thrust/Challenge Leads: *Mary Crawford, Andy Armstrong, Art Fischer, Eric Shaner, George Wang, Jim Martin*


Courtesy, Fred Schubert, RPI


Earth at Night NASA


http://www.american-pictures.com/gallery/usa/images/usa-00454.jpg

Helping build the scientific foundation that enables the most light for the least energy, throughout the world

Work at Sandia National Laboratories was supported by Sandia's Solid-State-Lighting Science Energy Frontier Research Center, funded by the U.S. Department of Energy, Office of Basic Energy Sciences. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.
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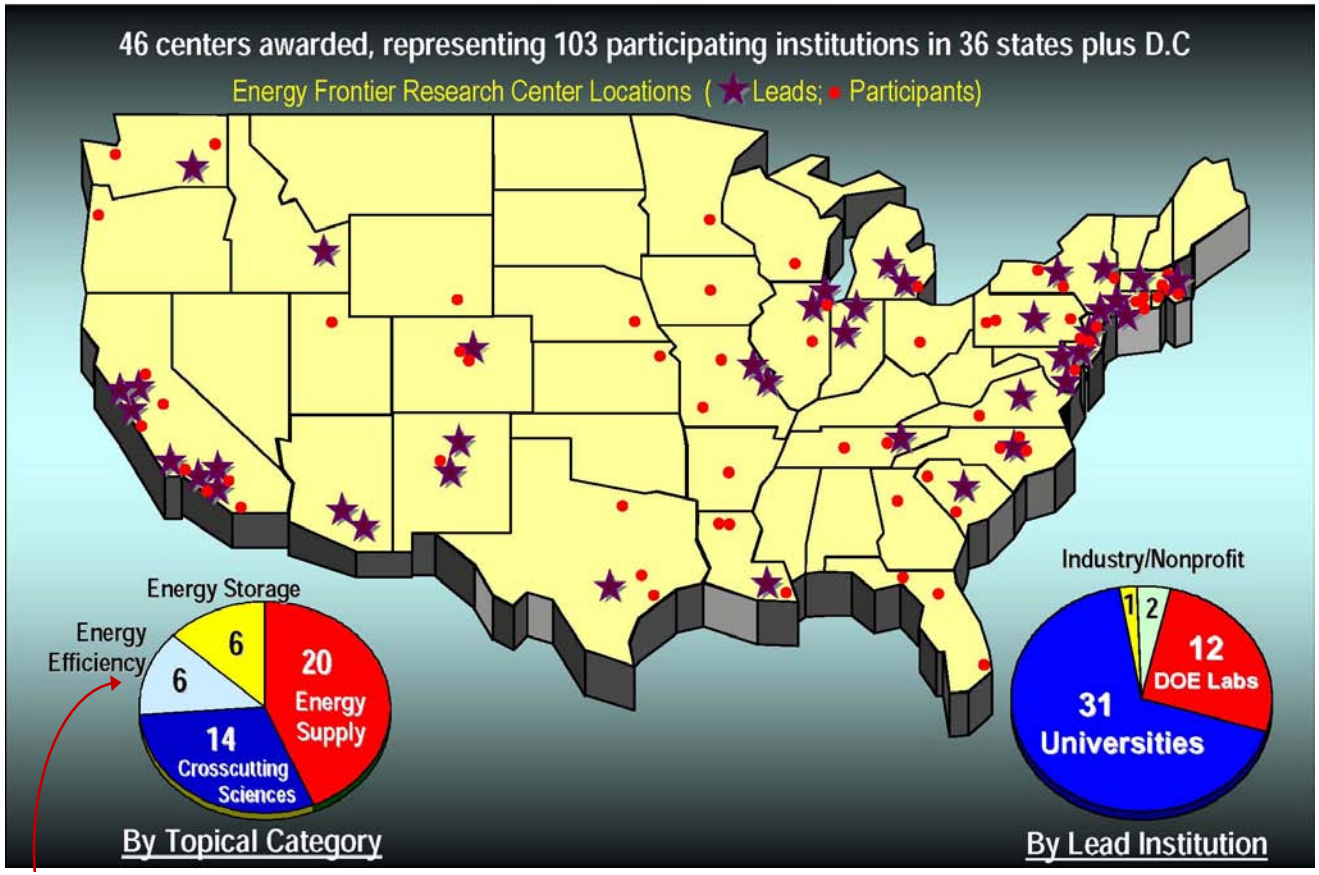
We are one of 46 Department of Energy Office of Science EFRCs



- **Goal: To establish the scientific foundation for a fundamentally new U.S. energy economy**
- **Overall Budget: $777M over 5 years beginning Aug 2009**
- **Our Budget: $18M over 5 years**

We are one of 6 EFRCs focused on efficiency, and the only one focused on SSL

Our EFRC aims to:

Science ⟷ Technology

1 Deepen the foundational science
- underlying SSL technology
- while informing, and being informed by, SSL technology

2 Create an environment which
- brings together critical mass of world-class scientists & resources collaborating synergistically (more than the sum of its parts)
- allows us to "follow our noses" without micromanagement

3 Share knowledge *actively* with
- specialists (scientists, technologists)
- non-specialists (students, public, gov't)

People & Resources: March 2011 Snapshot (33+20)

Management Team
Jerry Simmons
Mike Coltrin
Jeff Tsao

Thrust Leaders
Mary Crawford
Art Fischer
George Wang

Senior Staff
Andy Armstrong
Bob Biefeld
Igal Brener
Weng Chow
Jianyu Huang
Dan Koleske
Francois Leonard
Qiming Li
Willie Luk
Jim Martin
Normand Modine
May Nyman
Lauren Rohwer
Eric Shaner
Ganesh Subramania
Jon Wierer

Post-Docs & Students
Tania Henry
Emil Kadlec
Jeremy Wright

Business & Administrative
Rene Sells
Alyssa Christy
Chris Monroe
Katelynn Florentino

Technical Support
Jeff Figiel
Tony Coley
Kris Fulmer
Karl Westlake

Integrated Materials Research Lab

Center for Integrated Nanotechnologies

Microsystems Engineering Sciences & Applications Complex

University of New Mexico
Professor Steve Brueck
Sasha Neumann

Yale University
Professor Jung Han
Chris Yerino
Ben Leung

Northwestern University
Professor Lincoln Lauhon
Sonal Padalkar (PD)
Jim Riley

Los Alamos National Lab
Rohit Prasankumar
Prashanth Upadhya
Rohan Kekatpure (PD)
Minah Seo (PD)

Rensselaer Polytechnic Univ
Professor Fred Schubert
Di Zhu
Ahmed Noemaun
Qi Dai

University of Massachusetts
Professor Dan Wasserman
Troy Ribaudo

UC Merced
Professor David Kelley

Philips Lumileds
Mike Craven

Organizational Structure & Communications

Office of Basic Energy Sciences	
Director	Harriet Kung
Assoc Director, Materials Science & Engineering Division	Linda Horton
Program Manager, Energy Frontier Research Centers	Tof Carim
Program Point of Contact, "Yellow Group"	P Thiyagarajan

Monthly telecons

Management and Administrative Team	
Director	Jerry Simmons
Co-Director	Mike Coltrin
Chief Scientist	Jeff Tsao
Public Outreach, Office, Budget	Rene Sells, Alyssa Christy, Chris Monroe, Katelynn Florentino

Monthly lunches

Weekly Coffee/ Dessert Hours

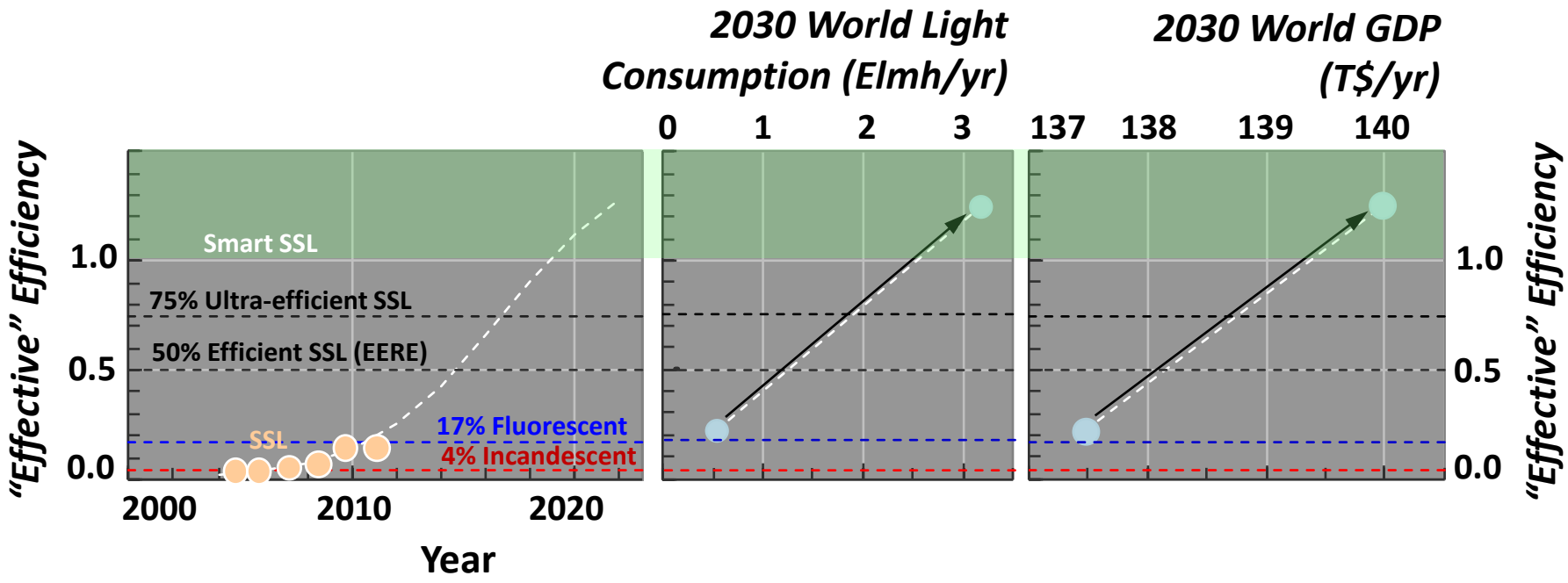
Thrust	1 Foundational Understanding	2 Beyond Spontaneous Emission	3 Beyond 2D
Lead	Mary Crawford	Art Fischer	George Wang
Sandia Staff	Andy Armstrong Normand Modine Weng Chow Dan Koleske	Igal Brener Willie Luk Ganesh Subramania Eric Shaner Jon Wierer Dan Koleske	Qiming Li Jianyu Huang Francois Leonard Jim Martin Lauren Rohwer May Nyman
External Partners	Fred Schubert RPI Mike Craven Philips Lumileds	Steve Brueck UNM Dan Wasserman U Mass Lowell	Jung Han Yale Lincoln Lauhon Northwestern Rohit Pransankumar LANL

Annual on-site review

External Advisory Board

Dan Dapkus
USC
Colin Humphreys
U Cambridge
Arto Nurmikko
Brown U
Tom Picraux
LANL
Jim Speck
UCSB
Fred Welsh
Radcliffe Advisors

Solid-State Lighting: where we are now and where we'd like to be



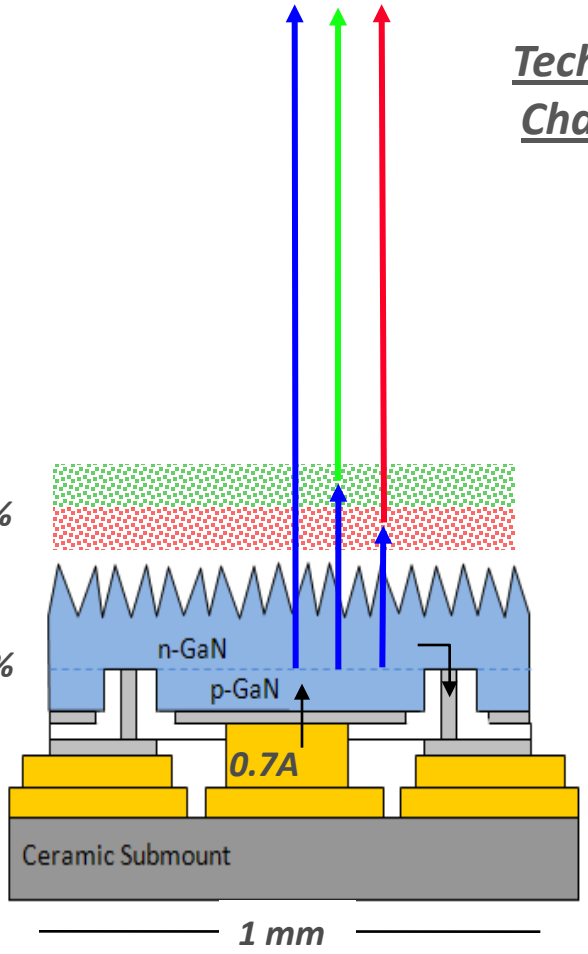
State-of-Art White Phosphor-Converted Light-Emitting Diode

78%

Efficiencies

54%

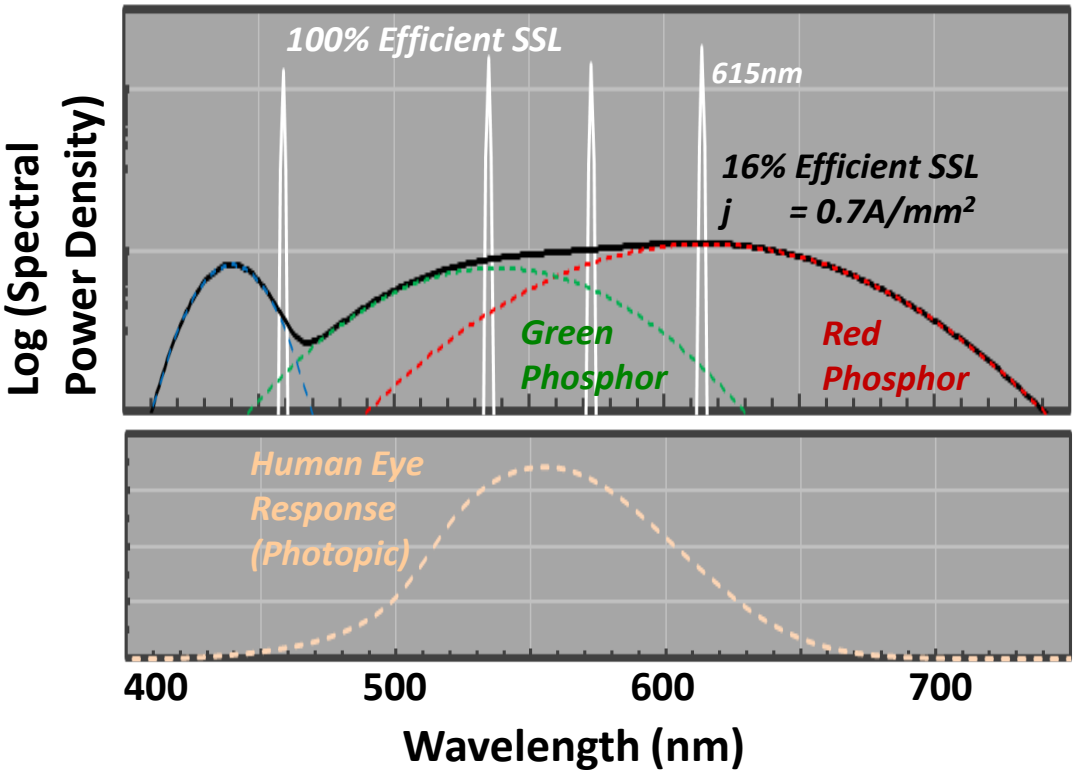
38%



Thin-Film Flip Chip (TFFC) schematic courtesy of Jon Wierer

Technology Challenges

1. *Blue LED efficiency droop*
2. *Stokes-deficit-free red & green light emitters*
3. *Narrow linewidth red phosphor*
4. *Non-Lambertian light*

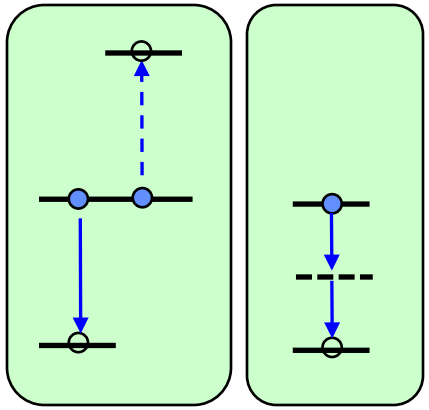


Sandia National Laboratories

Our EFRC's Scientific Thrusts

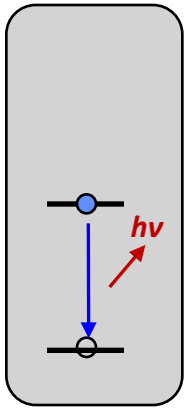
1 Competing Radiative and Non-Radiative Processes

Develop a microscopic understanding of the competition between radiative and non-radiative e-h recombination: spontaneous emission from planar structures.



Auger

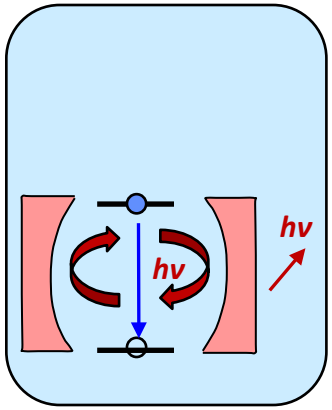
Shockley Read Hall



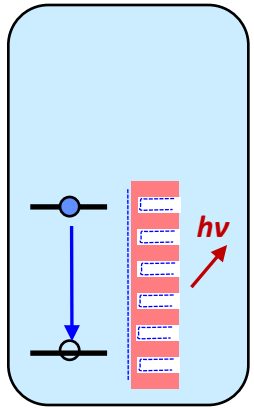
Spontaneous Band-Edge Emission

2 Beyond Free-Space Spontaneous Emission

Explore energy conversion routes that short-circuit conventional spontaneous emission but end in free-space photons.



Stimulated Emission and Strong Coupling



Plasmonic Intermediaries

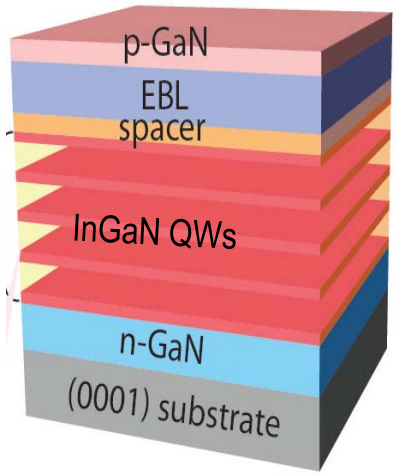
3 Beyond-2D

Explore the use of non-planar nanoscale structures to modify energy conversion routes so that they may be (a) isolated and better understood, and (b) engineered and optimized.

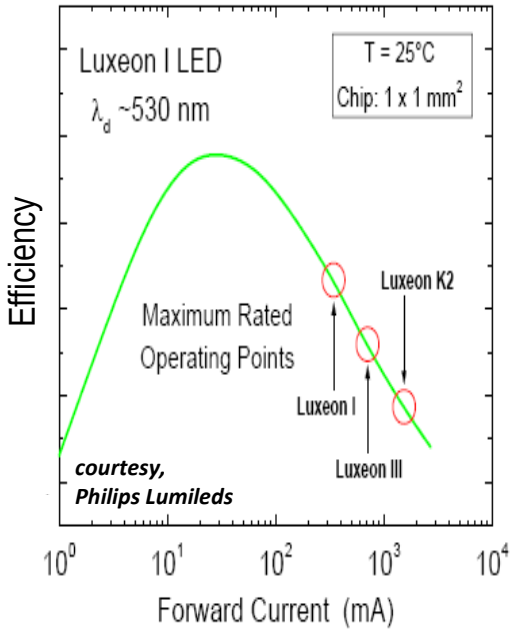
Mary Crawford (PI)
Weng Chow, Dan Koleske
Andy Armstrong, Normand Modine
Fred Schubert

1 Origin of Efficiency Droop: Beyond the A,B,C Approximation

Typical Light-Emitting Diode Heterostructure



Macroscopic observable



Usual "Macroscopic" A,B,C Approximation

Extraction efficiency
(photon trapping and absorption)

ε_{Joule}
Joule efficiency
(resistive losses)

ε_{IQE} Internal
quantum efficiency

$$\varepsilon = \left(\frac{V_{ph}}{V_{ph} + IR} \right) \cdot \varepsilon_{inj} \cdot \frac{BN^2}{AN + BN^2 + CN^3 + \ldots} \cdot \varepsilon_{ext}$$

2.8V 0.6Ω

Injection efficiency
(carrier overshoot/escape)

Shockley-Read-Hall
(defect-mediated)

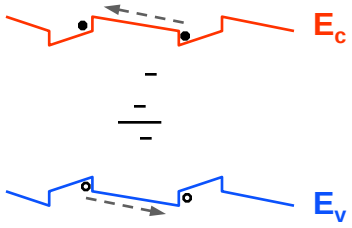
Spontaneous Emission

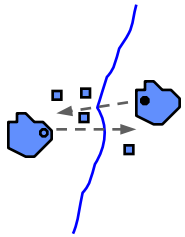
Auger-like

Mary Crawford (PI)
Weng Chow, Dan Koleske, Andy Armstrong, Normand Modine
Fred Schubert

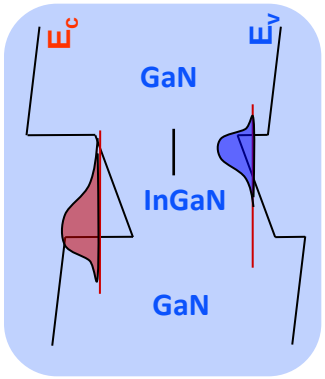
1 Microscopic View:
Carriers aren't identical, but are distributed

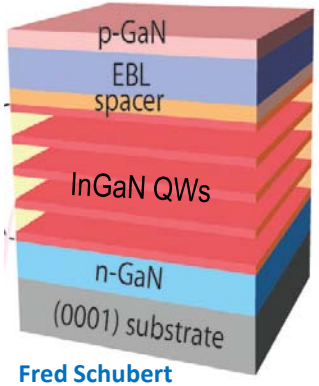
over xy-plane (bandgap inhomogeneities)





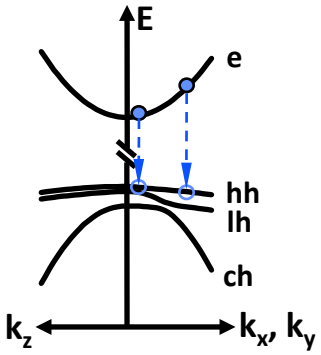
along z-axis (polarization fields and imperfect transport)

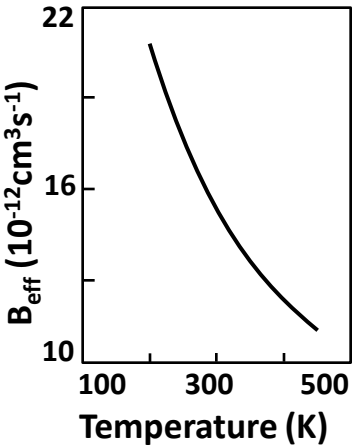




Fred Schubert
Mary Crawford

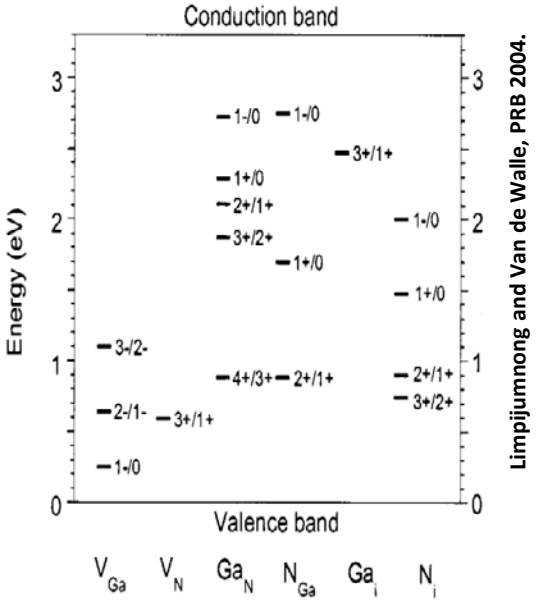
in k-space (plasma heating)





Weng Chow

over deep-level charge states (Fermi level changes)

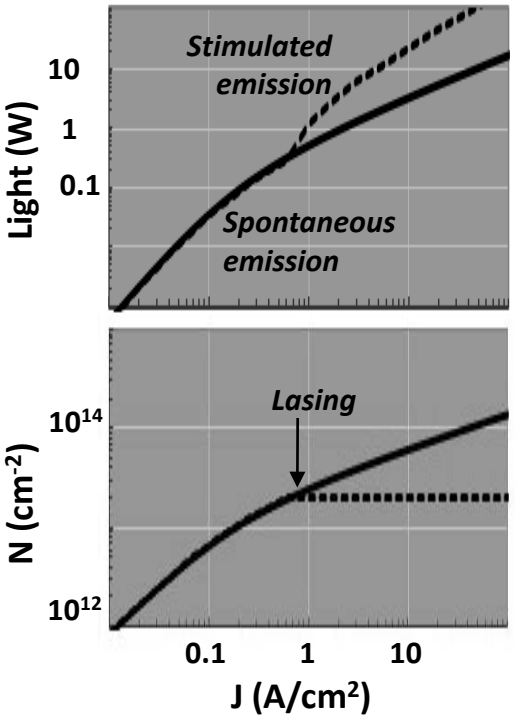


Andy Armstrong
Normand Modine
Weng Chow
Mary Crawford

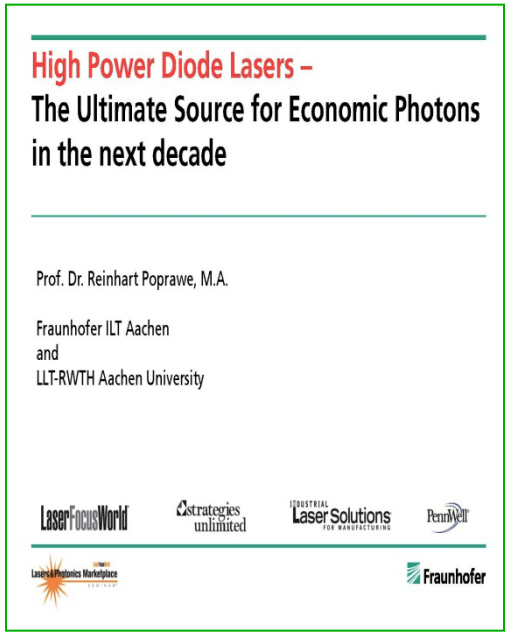
Jeff Tsao (PI)
Jon Wierer
Steve Brueck, Sasha Neumann
Wendy Davis, Yoshi Ohno

2 Beyond Free-Space Spontaneous Emission: Stimulated Emission

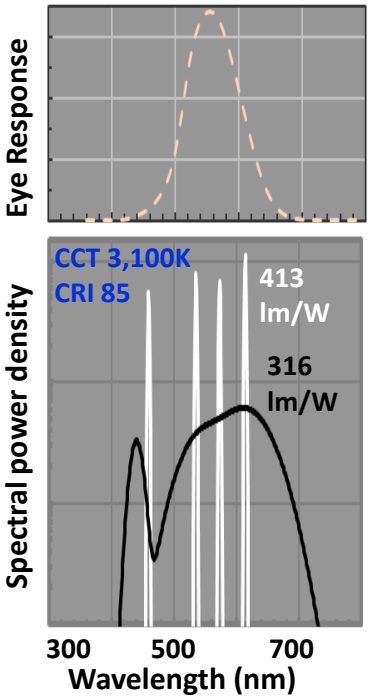
Stimulated emission clamps carrier densities and may circumvent droop



High current density enables cheap photons



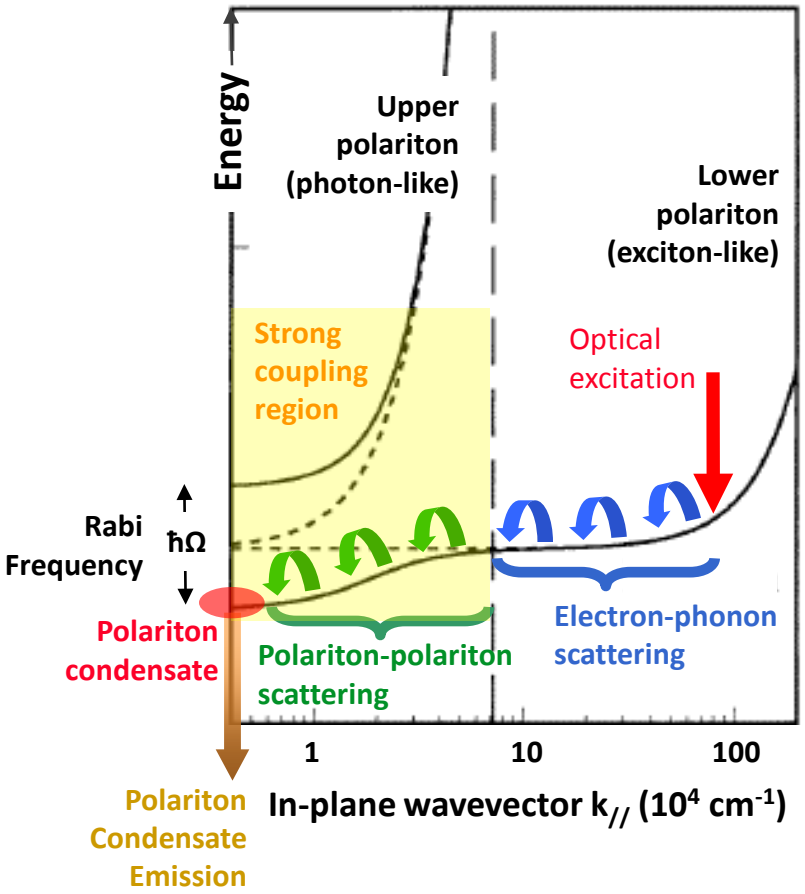
Narrow linewidths give high LER



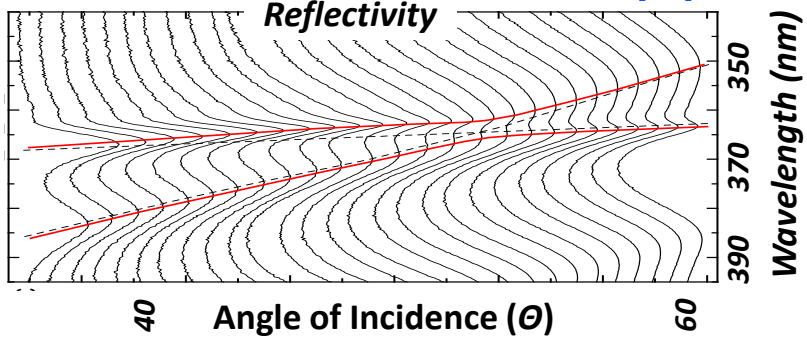
without sacrificing color quality

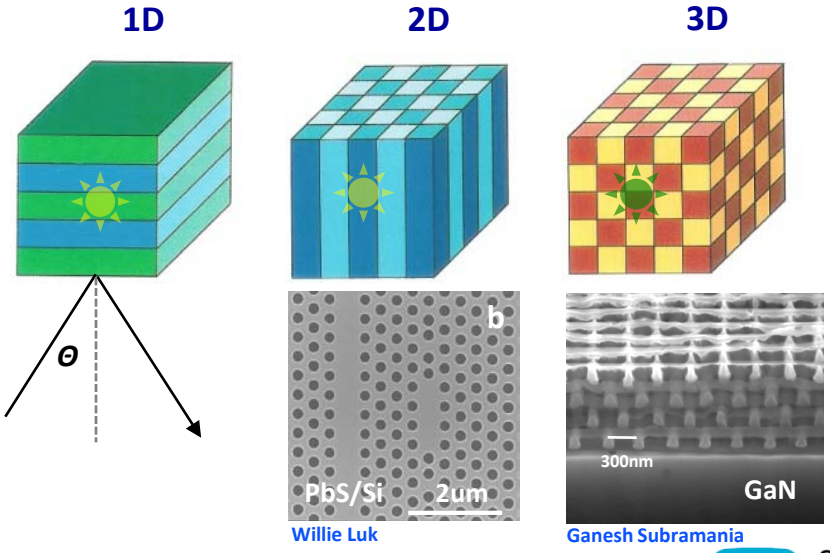
Art Fischer (PI)
Ganesh Subramania
Willie Luk, Weng Chow
Dan Koleske

2 Beyond Free-Space Spontaneous Emission: Altering Free Space



Art Fischer (Reflectance from GaN in HfO_2/SiO_2 DBR cavity)





Willie Luk

Ganesh Subramania

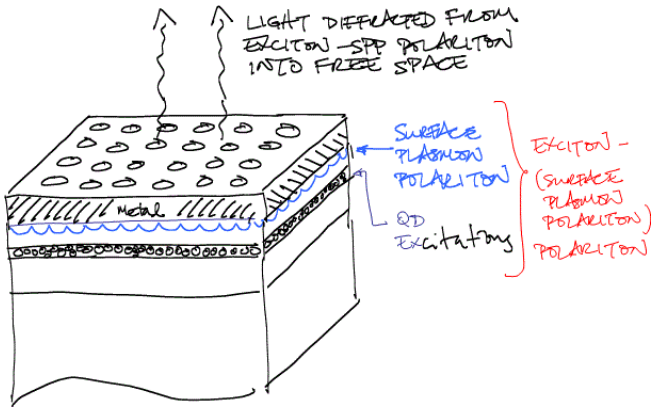
Eric Shaner (PI)
Dan Wasserman, Weng Chow

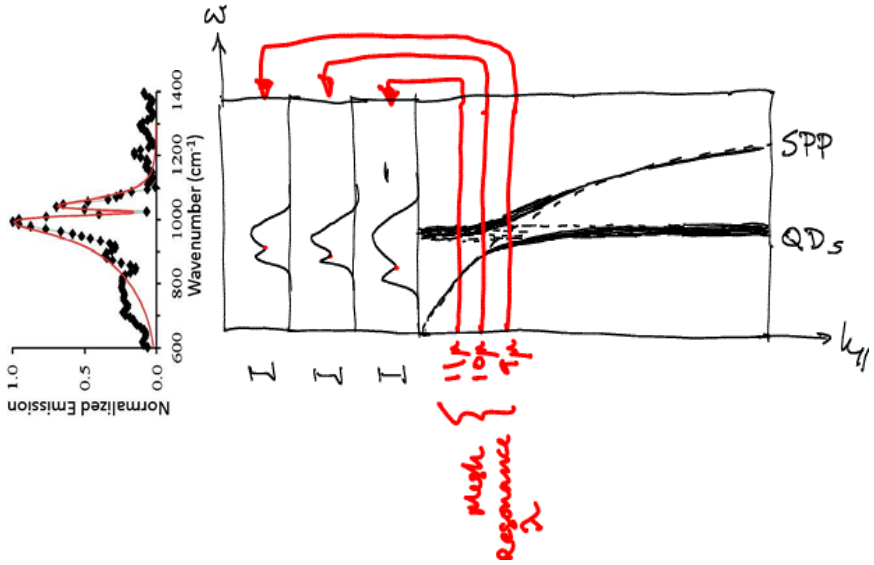
2 Other Polaritons to Exploit: (QD Excitation) - (Surface Plasmon) Polaritons

Can excitons be coupled effectively to surface-plasmon polaritons?

Yes! At least in the infrared, where metals are good, and lithography is easy

Challenge: moving to the visible



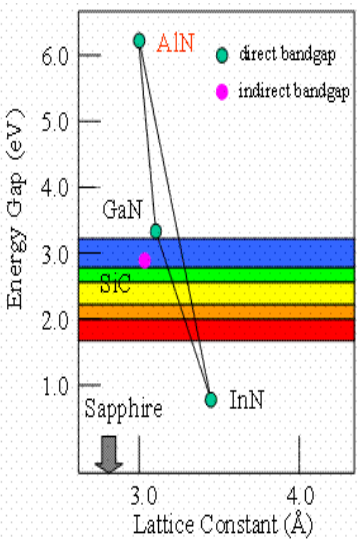


WL Barnes, et al, "Surface plasmon subwavelength optics," Nature 424, 824 (2003).

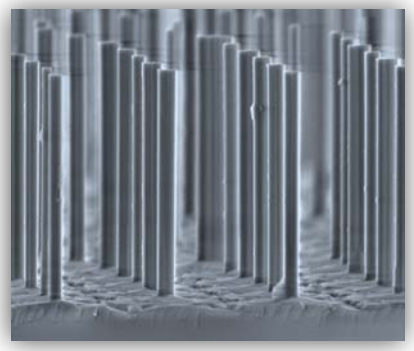
George Wang (PI)
Qiming Li, Jianyu Huang
Igal Brener, Jeremy Wright,
Francois Leonard
Rohit Prasankumar
Lincoln Lauhon

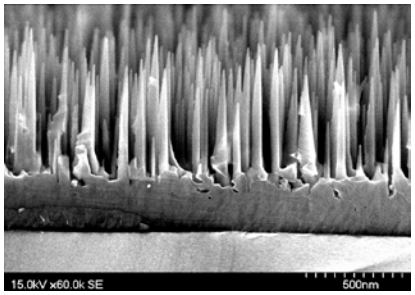
3 Beyond 2D: 1D Nanowire Synthesis, Properties, Architectures

High InGaN compositions needed to span SSL wavelengths



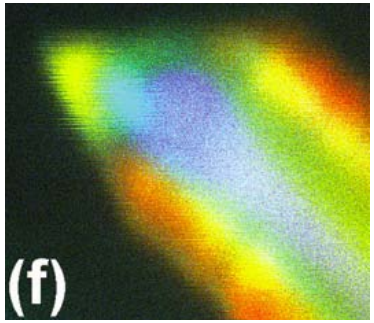
High aspect ratio enables strain accommodation

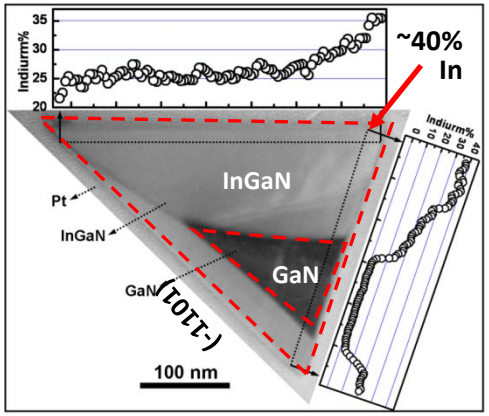




George Wang, Qiming Li

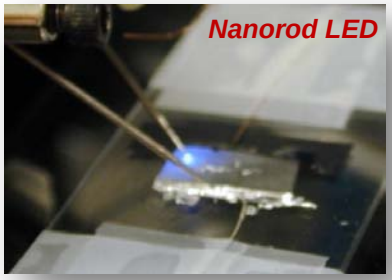
Measurements verify 40% InGaN, with anisotropies

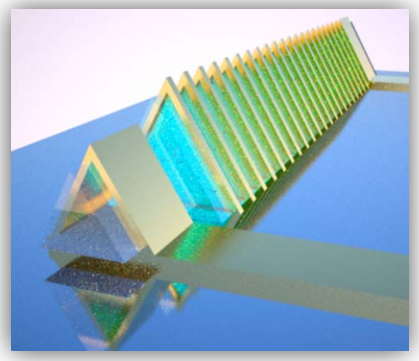




George Wang, Qiming Li

Future work: InGaN nanowire LEDs and lasing!





Igal Brener, Jeremy Wright

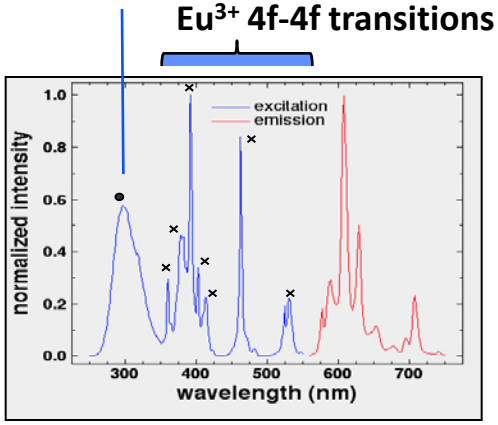
Jim Martin (PI)
Lauren Rohwer
May Nyman
David Kelley

3 Further Beyond 2D: 0D Atom and Dot Synthesis, Properties, Architectures

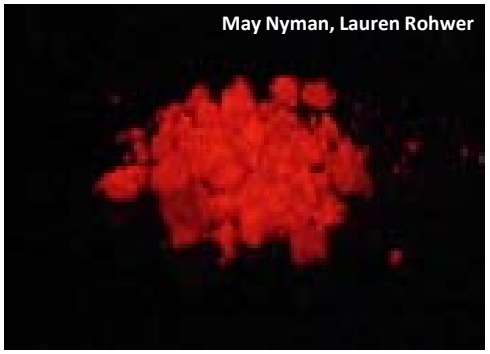
Eu^{3+} Phosphors

The challenge: blue absorption

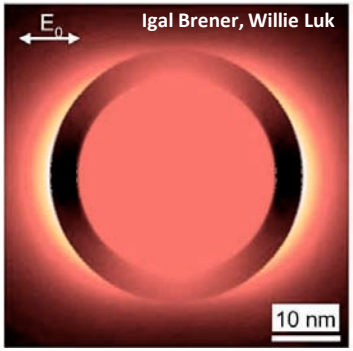
Eu-O, Ta-O charge transfer band
Eu^{3+} 4f-4f transitions



Eu^{3+}-doped rare earth tantalate pyrcholore

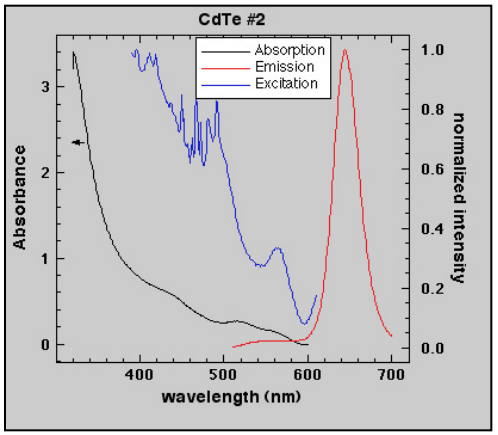


Plasmon-enhanced absorption & emission?

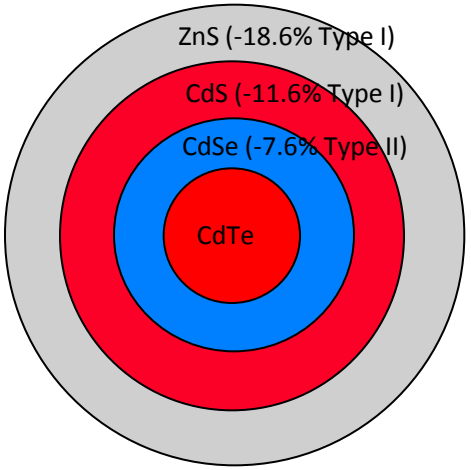


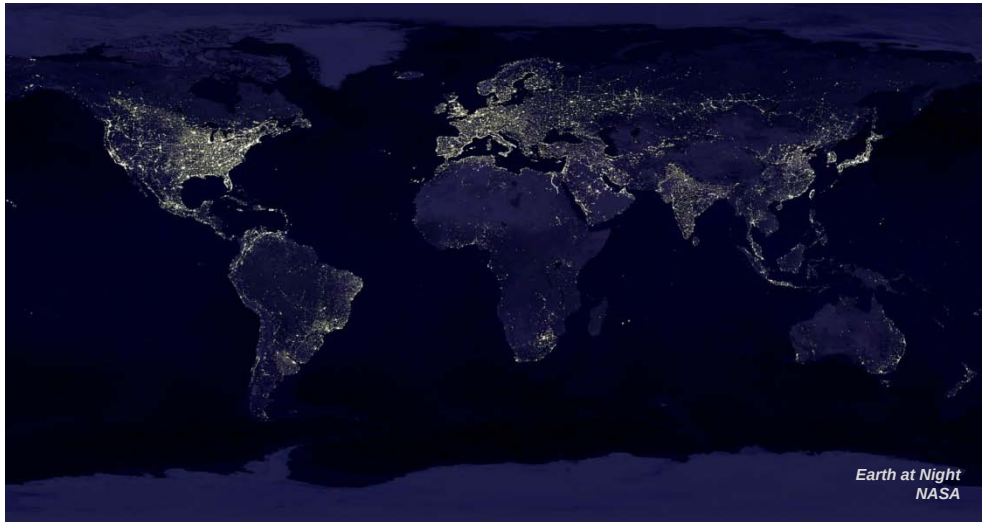
CdTe/CdSe Quantum Dots

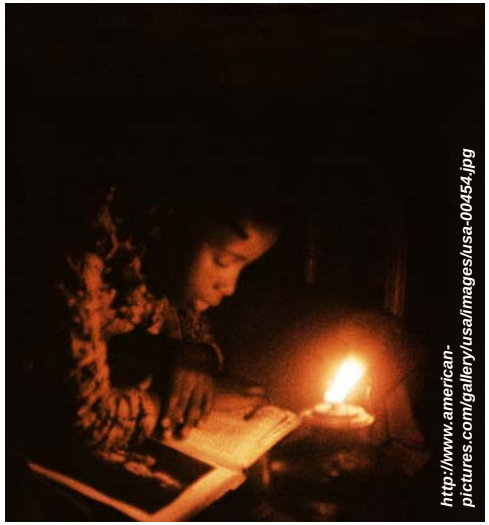
The challenge: a Type II heterostructure (reduced Auger recombination), capped by ZnS (reduced photo-degradation), but highly strained



Jim Martin, Lauren Rohwer







Helping build the scientific foundation that enables the most light for the least energy, throughout the world