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

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.

SAND 2011-2898 C
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:

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)

Integrated Materials Research Lab

Center for Integrated Nanotechnologies

Microsystems Engineering Sciences & Applications Complex

Management Team
Jerry Simmons
Mike Coltrin
Jeff Tsao
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 Subramaniam
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

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
Phlips Lumileds

Mike Craven
### Organizational Structure & Communications

#### Office of Basic Energy Sciences

<table>
<thead>
<tr>
<th>Role</th>
<th>Name</th>
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<tbody>
<tr>
<td>Director</td>
<td>Harriet Kung</td>
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<tr>
<td>Assoc Director, Materials Science &amp; Engineering Division</td>
<td>Linda Horton</td>
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<tr>
<td>Program Manager, Energy Frontier Research Centers</td>
<td>Tof Carim</td>
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<tr>
<td>Program Point of Contact, “Yellow Group”</td>
<td>P Thiyagarajan</td>
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#### Management and Administrative Team

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<tr>
<td>Public Outreach, Office, Budget</td>
<td>Rene Sells, Alyssa Christy, Chris Monroe, Katelynn Florentino</td>
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#### Thrusts

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<th>Thrust</th>
<th>1 Foundational Understanding</th>
<th>2 Beyond Spontaneous Emission</th>
<th>3 Beyond 2D</th>
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<tr>
<td>Lead</td>
<td>Mary Crawford</td>
<td>Art Fischer</td>
<td>George Wang</td>
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<td>Sandia Staff</td>
<td>Andy Armstrong</td>
<td>Igal Brener, Willie Luk, Ganesh Subramania, Eric Shaner, Jon Wierer, Dan Koleske</td>
<td>Qiming Li, Jianyu Huang, Francois Leonard, Jim Martin, Lauren Rohwer, May Nyman</td>
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<tr>
<td>External Partners</td>
<td>Fred Schubert</td>
<td>Steve Brueck, UNM, Dan Wasserman, U Mass Lowell</td>
<td>Jung Han, Yale, Lincoln Lauhon, Northwestern, Rohit Pransankumar, LANL</td>
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**Monthly telecons**

**Monthly lunches**

**Weekly Coffee/Dessert Hours**

**Management and Administrative Team**

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**External Advisory Board**

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<tr>
<th>Board Member</th>
<th>Institution</th>
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<tr>
<td>Dan Dapkus</td>
<td>USC</td>
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<td>Colin</td>
<td>Humphreys</td>
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<td>Arto Nurmikko</td>
<td>U Cambridge</td>
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<td>Tom Picraux</td>
<td>Brown U</td>
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<td>LANL</td>
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<td>Jim Speck</td>
<td>UCSB</td>
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<tr>
<td>Fred Welsh</td>
<td>Radcliffe Advisors</td>
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**Annual on-site review**
Solid-State Lighting: where we are now and where we’d like to be

"Effective" Efficiency

2030 World Light Consumption (Elmh/yr)

0 1 2 3

137 138 139 140

"Effective" Efficiency

2030 World GDP (T$/yr)

50% Efficient SSL (EERE)
75% Ultra-efficient SSL
Smart SSL

"Effective" Efficiency

Year

2000 2010 2020

4% Incandescent
17% Fluorescent
State-of-Art White Phosphor-Converted Light-Emitting Diode

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

Efficiencies:
- 100% Efficient SSL
- 615nm
- 16% Efficient SSL
- $j = 0.7A/mm^2$

Wavelength (nm)

Log (Spectral Power Density)

Human Eye Response (Photopic)

Thin-Film Flip Chip (TFFC) schematic courtesy of Jon Wierer
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.
1 Origin of Efficiency Droop: Beyond the A,B,C Approximation

Typical Light-Emitting Diode Heterostructure

Macroscopic observable

Efficiency

Injection efficiency (carrier overshoot/escape)

Spontaneous Emission

Shockley-Read-Hall (defect-mediated)

Usual “Macroscopic” A,B,C Approximation

Extraction efficiency (photon trapping and absorption)

Joule efficiency (resistive losses)

Internal quantum efficiency

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

Typical Light-Emitting Diode Heterostructure:
- p-GaN
- EBL spacer
- InGaN QWs
- n-GaN (0001) substrate

Efficiency vs. Forward Current (mA)

Luxeon I LED
- \( \lambda_d \approx 530 \text{ nm} \)
- T = 25°C
- Chip: 1 x 1 mm²

Maximum Rated Operating Points:
- Luxeon I
- Luxeon K2
- Luxeon III

Efficiency graph:
- 10⁰, 10¹, 10², 10³, 10⁴

Efficiency graph courtesy, Philips Lumileds

Usual “Macroscopic” A,B,C Approximation:
- Injection efficiency
- Extraction efficiency
- Joule efficiency
- Shockley-Read-Hall (defect-mediated)
- Spontaneous Emission
- Auger-like

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Maximum Rated Operating Points:
- Luxeon I
- Luxeon K2
- Luxeon III

Efficiency graph courtesy, Philips Lumileds
Carriers aren’t identical, but are distributed

over xy-plane (bandgap inhomogeneities)
along z-axis (polarization fields and imperfect transport)
in k-space (plasma heating)
over deep-level charge states (Fermi level changes)

Fred Schubert
Mary Crawford

Limpijumnong and Van de Walle, PRB 2004.

Andy Armstrong
Normand Modine
Weng Chow
Mary Crawford
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.


Prof. Dr. Reinhart Poprawe, M.A.
Fraunhofer ILT Aachen
and
ILT-RWTH Aachen University

CCT 3,100K
CRI 85
413 lm/W
316 lm/W

Spectral power density
Wavelength (nm)
300 500 700

Eye Response

Jeff Tsao (PI)
Jon Wierer
Steve Brueck, Sasha Neumann
Wendy Davis, Yoshi Ohno
Beyond Free-Space Spontaneous Emission: Altering Free Space

- Polariton condensate
- Polariton-polariton scattering
- Electron-phonon scattering
- In-plane wavevector $k_\parallel$ ($10^4$ cm$^{-1}$)

- Strong coupling region
- Upper polariton (photon-like)
- Lower polariton (exciton-like)

- Rabi frequency $\hbar \Omega$
- Reflectivity
- Angle of Incidence ($\Theta$)
- Wavelength (nm)
- Polariton condensate emission

- 1D, 2D, 3D spatial dimensions
- Reflectance from GaN in HfO$_2$/SiO$_2$ DBR cavity

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

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

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

**High InGaN compositions needed to span SSL wavelengths**

**High aspect ratio enables strain accommodation**

**Measurements verify 40% InGaN, with anisotropies**

**Future work: InGaN nanowire LEDs and lasing!**

Future work: InGaN nanowire LEDs and lasing!
3 Further Beyond 2D: 0D Atom and Dot Synthesis, Properties, Architectures

Eu³⁺ Phosphors
The challenge: blue absorption

Eu-O, Ta-O charge transfer band Eu³⁺ 4f-4f transitions

Eu³⁺-doped rare earth tantalate pyrochlore

Plasmon-enhanced absorption & emission?

Eu³⁺ Phosphors

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

CdTe/CdSe Quantum Dots

ZnS (-18.6% Type I)
CdS (-11.6% Type I)
CdSe (-7.6% Type II)
CdTe
Helping build the scientific foundation that enables the most light for the least energy, throughout the world