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# The Solid State Lighting Program at Sandia National Laboratories

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**Sandia National Laboratories**

*Sandia Solid State Lighting*

SSL

*Illumination through semiconductor science*

SSLS EFRC

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Office of Basic Energy Sciences • Serving the Present, Shaping the Future •

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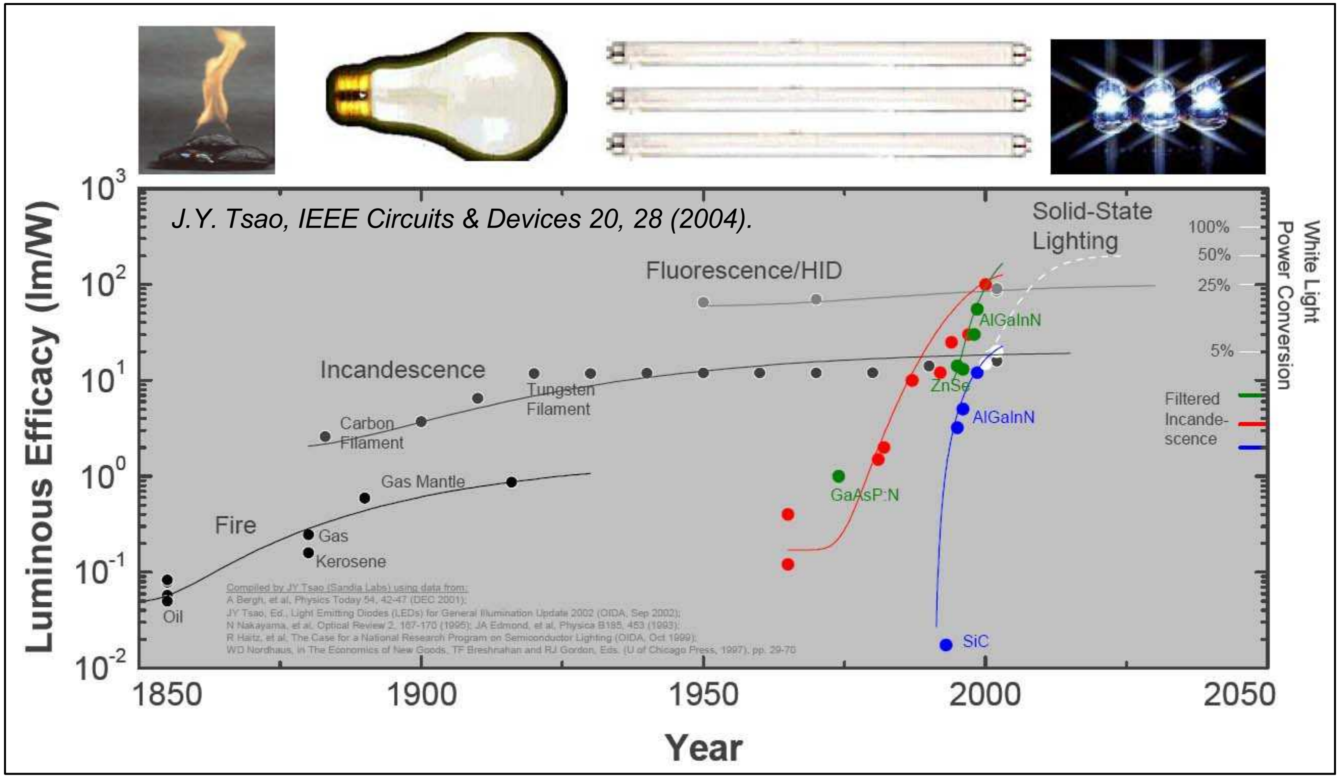
# Outline

1. Why Solid-State Lighting (SSL)
2. U.S. Department of Energy (DOE) SSL Initiative
3. National Center for SSL (DOE Office of Energy Efficiency and Renewable Energy)
4. Energy Frontier Research Center for Solid State Lighting Science
5. Current SSL Research & Development (R&D)

# Why Solid State Lighting?

*Luminous efficacy from conventional light sources has stagnated for the last 50 years*




**Power Conversion Efficiency**

**Incandescent ~4%**

**Fluorescent ~ 18%**

**SSL Goal ~ 50%**

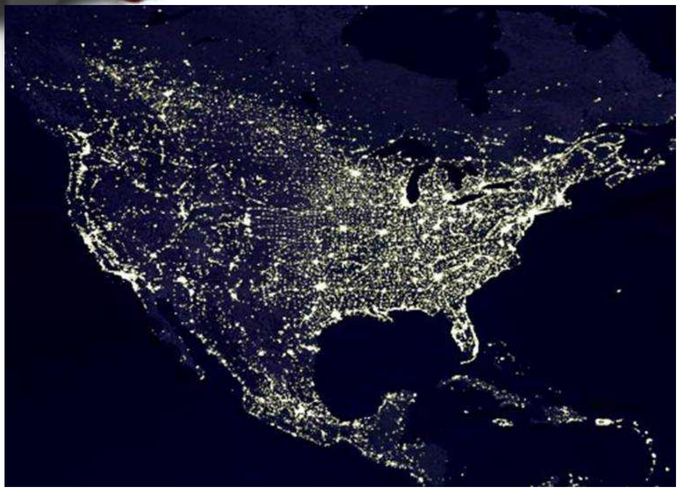
**LED package mid 1990's**

**Lumileds 5 W package, 2009**

***DOE has a stated goal of producing SSL with 50% wall-plug efficiency by 2025 ( ~ 230 lm/W )***

**In August 2010, Nichia reported a 249 lm/W cool white LED.**

# Motivation for Solid-State Lighting



- ~22% of electricity consumption is for general illumination
- Lighting is one of the most ***inefficient*** energy technologies in buildings → opportunity!
- Achieving 50% efficient lighting would have tremendous global impact:
  - decrease electricity consumed by lighting by > 50%
  - decrease total electricity consumption by 10%

**Efficiencies of energy technologies in buildings:**

| | |
|---|---|
| Heating: | 70 - 80% |
| Elect. motors: | 85 - 95% |
| Fluorescent: | 20-25% |
| Incandescent: | ~3-5% |

US DOE target: 50%
"Ultra-efficient" SSL*: ≥ 70%

| Projected Year 2025 Savings | US | World |
|---|---|---|
| Electricity used (TW-hr) | 620/year | ~2,000/year |
| $ spent on Electricity | 42B/year | ~150B/year |
| Electricity generating capacity (GW) | 75 | ~250 |
| Carbon emissions (Mtons/year) | 100 | ~350 |

* *J. Phillips et al., Laser and Photonics Review, 2007*

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# 1999-2001:
# Sandia helps catalyze national Interest in SSL

## THE CASE FOR A NATIONAL RESEARCH PROGRAM ON SEMICONDUCTOR LIGHTING[1,2]

Roland Haitz and Fred Kish, Hewlett-Packard Company, Palo Alto, CA 94304
Jeff Tsao and Jeff Nelson, Sandia National Laboratories, Albuquerque, NM 87185-0601

### EXECUTIVE SUMMARY

Dramatic changes are unfolding in lighting technology. Semiconductor light emitting diodes (LEDs), until recently used mainly as simple indicator lamps in electronics and toys, have become as bright and efficient as incandescent bulbs, at nearly all visible wavelengths. They have already begun to displace incandescent bulbs in many applications, particularly those requiring durability, compactness, cool operation and/or directionality (e.g., traffic, automotive, display, and architectural/directed-area lighting).

Further major improvements in this technology are believed achievable. Recently, external electrical-to-optical energy conversion efficiencies exceeding 50% have been achieved in infrared light emitting devices. If similar efficiencies are achieved in the visible, the result would be the holy grail of lighting: a 200*lm/W* white light source two times more efficient than fluorescent lamps, and ten times more efficient than incandescent lamps.

*This new white light source would change the way we live, and the way we consume energy.* The worldwide amount of electricity consumed by lighting would decrease by more than 50%, and total worldwide consumption of electricity would decrease by more than 10%. The global savings would be more than 1,000*TWh/yr* of electricity at a value of about US$100B/year, along with the approximately 200 million tons of carbon emissions created during the generation of that electricity. Moreover, more than 125*GW* of electricity generating capacity would be freed for other uses or would not need to be created, a savings of over US$50B of construction cost.

Bringing about such revolutionary improvements in performance will require a concerted national effort, of the order $0.5B over ten years, tackling a broad set of issues in semiconductor lighting technology. The effort would also require harnessing the most advanced high-technology companies, the best national laboratory resources, and the most creative university researchers in this area.

Fire — Candles and Lamps — Bulbs and Tubes — Semiconductors

[1] This white paper was first presented publicly at the 1999 Optoelectronics Industry Development Association (OIDA) forum in Washington DC on October 6, 1999.

[2] Revision B:03/30/1999





107TH CONGRESS
1ST SESSION

# S. 1166

To establish the Next Generation Lighting Initiative at the Department of Energy, and for other purposes.

IN THE SENATE OF THE UNITED STATES

JULY 11, 2001

Mr. BINGAMAN (for himself and Mr. DEWINE) introduced the following bill; which was read twice and referred to the Committee on Energy and Natural Resources

# A BILL

To establish the Next Generation Lighting Initiative at the Department of Energy, and for other purposes.

*Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,*

**SECTION 1. SHORT TITLE.**

This Act may be cited as "Next Generation Lighting Initiative Act".

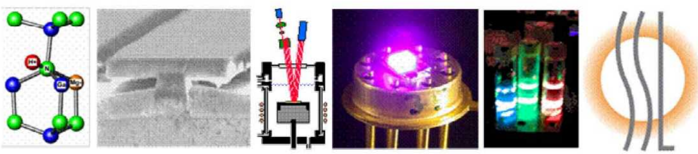
**SEC. 2. FINDING.**

Congress finds that it is in the economic and energy security interests of the United States to encourage the development of white light emitting diodes by providing financial assistance to firms, or a consortium of firms, and

# 2000-2004:Sandia's Grand Challenge LDRD

SAND 2004-2365
UNLIMITED RELEASE
PRINTED MAY 2004

Final Report on Grand Challenge LDRD Project:



A Revolution in Lighting –
Building the Science and Technology Base
for Ultra-Efficient Solid-State Lighting

Solid-State Lighting GCLDRD Final Report    Page 3 of 151

**Goals of GC-LDRD:**

1. **Help establish the fundamental science and technology base for SSL.**
2. **Develop the technology infrastructure of Gallium Nitride (GaN) material sciences for synergistic national security needs.**

**By the end of FY04, this project had invested ~$8M in Solid-State Lighting.**

**Built on our investment of *a few $100 M in compound semiconductor technology* over the past two decades.**

# In 2000 we started "A Revolution in Lighting": Sandia's Grand Challenge LDRD

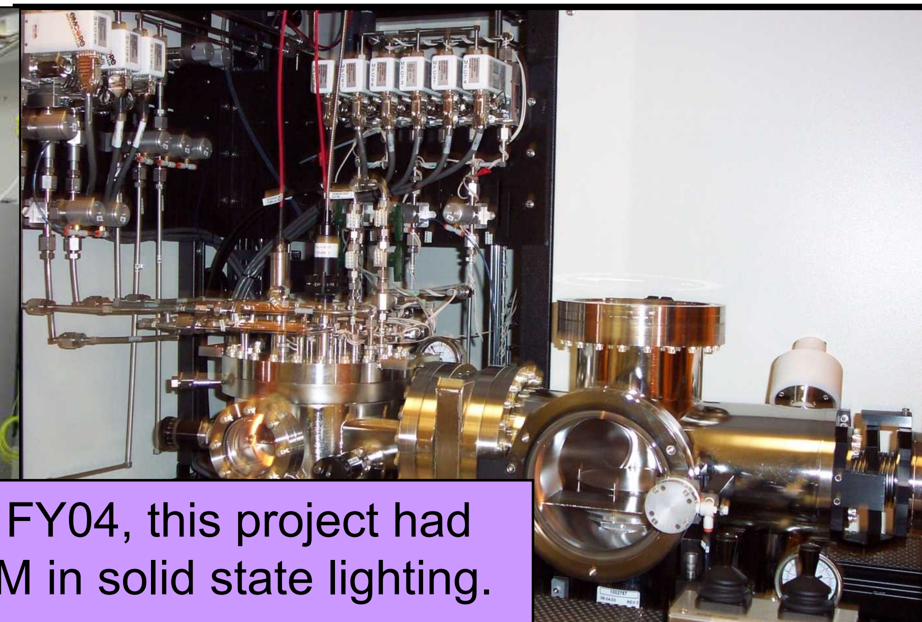
Goals of the Grand Challenge LDRD (Laboratory Directed R&D) Project:

1. Help establish the fundamental science and technology base for SSL.
2. Develop the technology infrastructure of gallium nitride (GaN) material sciences for synergistic national security needs.

Advanced Nanotechnology Tool (ANT)

At the end of FY04, this project had invested ~$8M in solid state lighting.

Builds on Sandia's investment of **a few $100 M in compound semiconductor technology** over the past two decades.



GaN MOCVD System

# 2001-DOE/Office of Energy Efficiency and Renewable Energy develops an SSL program

**DOE/EERE Solid-State Lighting Program Goal**

*By 2025, develop advanced solid state lighting technologies that, compared to conventional lighting technologies, are much more energy efficient, longer lasting, and cost-competitive, by targeting a product system efficiency of 50 percent with lighting that accurately reproduces the sunlight spectrum.*

***http://www.netl.doe.gov/ssl***

# The Energy Policy Act of 2005 is supportive of increased SSL R&D

## Subtitle A - Energy Efficiency

SEC. 912. NEXT GENERATION LIGHTING INITIATIVE

“The Secretary shall carry out a Next Generation Lighting Initiative in accordance with this section to support research, development, demonstration, and commercial application activities related to advanced solid-state lighting technologies based on white light emitting diodes.”

***Authorizes $50M/year for 2006 through 2013 (8 years)***

## Subtitle F: Science

SEC. 966. SOLID STATE LIGHTING

“The Secretary shall conduct a program of fundamental research on advanced solid state lighting in support of the Next Generation Lighting Initiative carried out under section 912.”

# Sec. Bodman announced the National Center for SSL at the DOE Nanoscale Science Research Centers


In 2006 Sandia was chosen as the lead lab for the National Center

# EFRC for Solid-State Lighting (SSL) Science

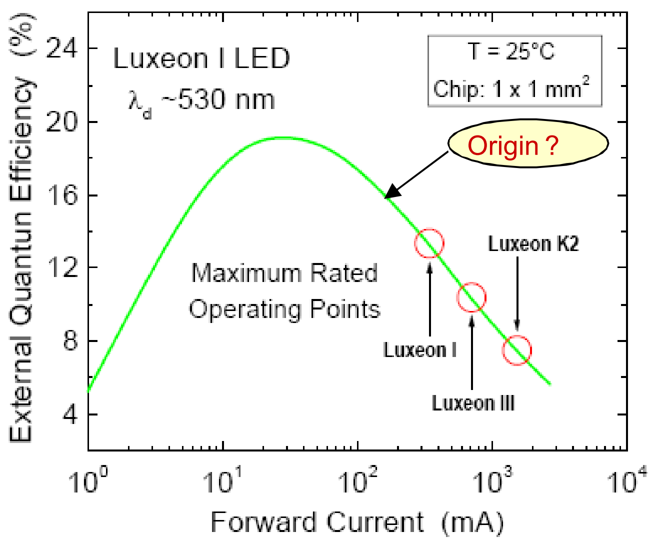
Jerry A. Simmons & Mike Coltrin
(Sandia National Labs, August 2009)

Goal: Improve the energy-efficiency in the way we light our homes and offices, which currently accounts for 20% of the nation's electrical energy use. Solid-State Lighting (SSL) has the potential to cut that energy consumption in half – or even more.


Research plan: Investigate conversion of electricity to light using radically new designs, such as luminescent nanowires, quantum dots, and hybrid architectures; study energy conversion processes in structures whose sizes are even smaller than the wavelength of light; understand and eliminate defects in SSL semiconductor materials that presently limit the energy efficiency.

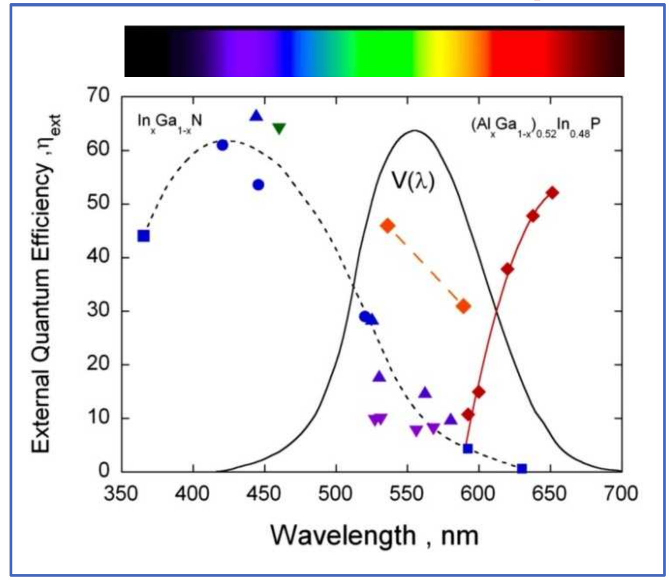
# Four major issues of InGaN-based SSL

## "Efficiency Droop"




Auger?
Phonon-assisted Auger?
Carrier leakage?

## "Green-Yellow Gap"



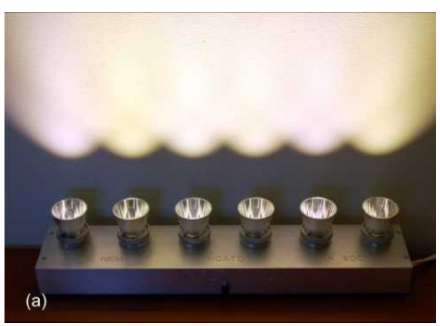

Needed for RGB or RYGB LED combination

Not necessary for blue + phosphor

## "Color Control"

Growth temperature influences indium concentration

Need better temperature control and uniformity.




Depending on the blue LED λ and the phosphor can get different color temperature.

Can be solved by matching LED and phosphor.

## "COST"

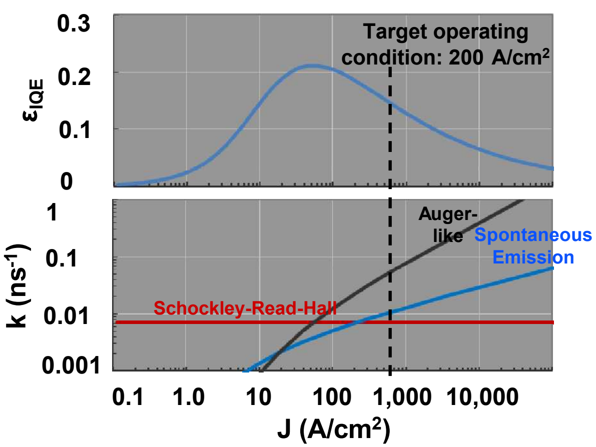
Has to be reduced by ~20x

7 Watt LED Light Bulb –
60 Watt Replacement
Reg Price: ~~$49.00~~ Spring Sale: $39.89

# Technology "Grand Challenges" for ultra-efficient SSL

## ① *Eliminate blue LED efficiency droop at high currents*

Internal quantum efficiency vs. current




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

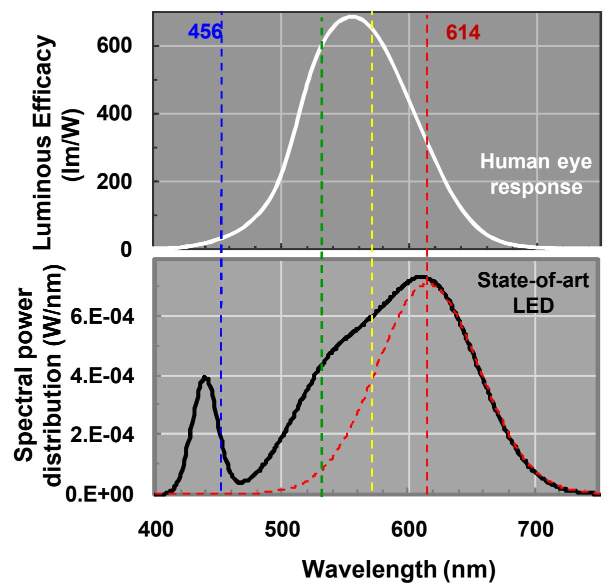
Shockley-Read-Hall

Spontaneous Emission

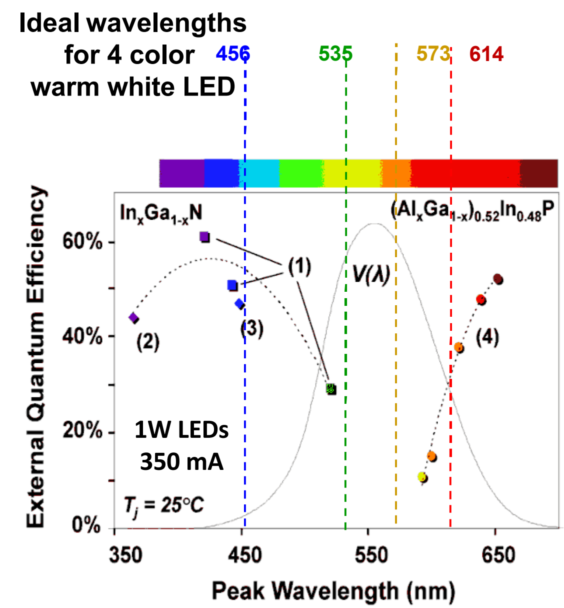
Auger-like

*Rate constants for 510nm LED, after UT Schwarz, "Emission of biased green quantum wells in time and wavelength domain," SPIE Proc 7216, 7216U-1 (2009).*

## ② *Narrow-linewidth shallow-red emitter*




## ③ *Fill in the green-yellow gap in LED efficiency*




*Courtesy of M. Krames, Philips-Lumileds*

SSLS EFRC SOLID-STATE LIGHTING SCIENCE ENERGY FRONTIER RESEARCH CENTER

Sandia National Laboratories

# Snapshots of Current Sandia's SSL R&D

# Energy Frontier Research Center for Solid-State Lighting Science

Wide-Bandgap Materials and Properties: Foundational Understanding and Beyond

Beyond 2D: Luminescent Nanowires, Nanodots, and Hybrid Structures

Beyond Perturbations: Light and Matter in Subwavelength Photonic Structures

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SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

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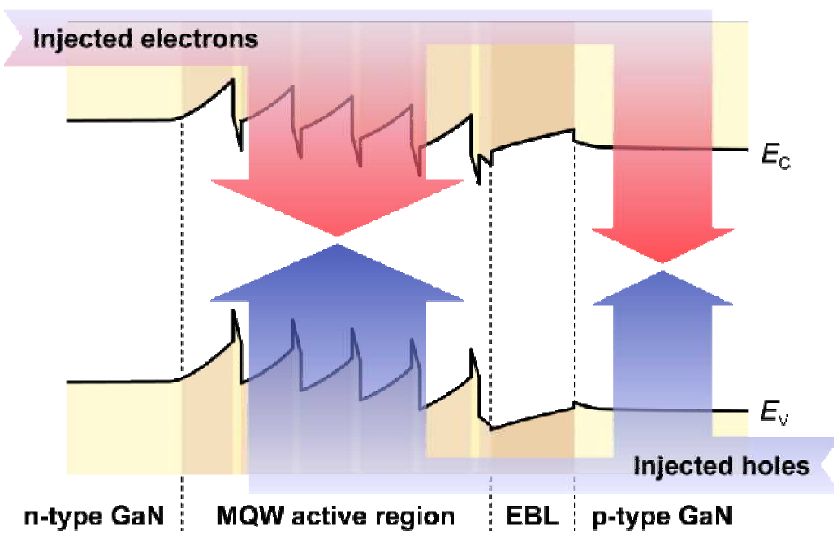
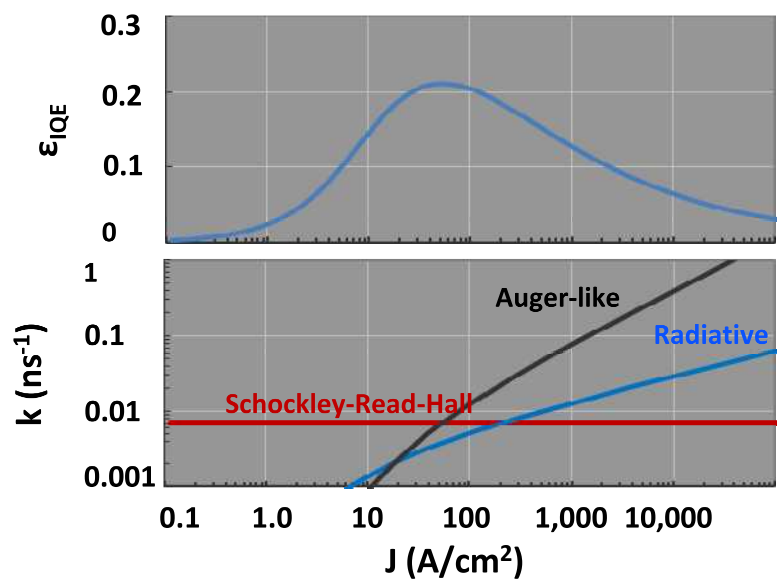
# EFRC Thrust 1: Foundational Understanding- Competing Energy Conversion Routes in Light-Emitting InGaN

*Carrier injection and transport pathways*




*Courtesy of Fred Schubert, RPI*

*Recombination pathways*




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

Shockley-Read-Hall (nonradiative at defects)

Radiative

Auger and higher order processes

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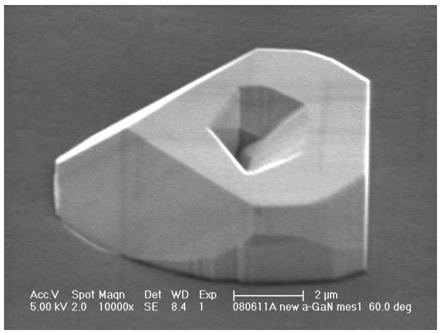
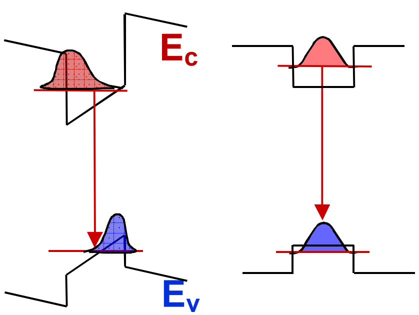
# EFRC Thrust 2: Beyond 2D

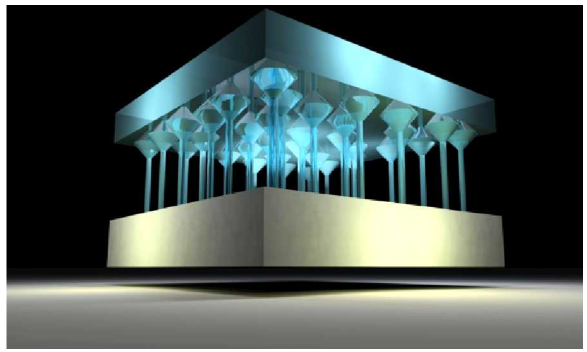
*Non-planar growth: routes to non-polar orientations*




*Courtesy Jung Han, Yale University*

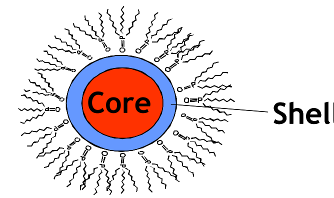



*Nanowires: a test bed for materials / luminescence studies*

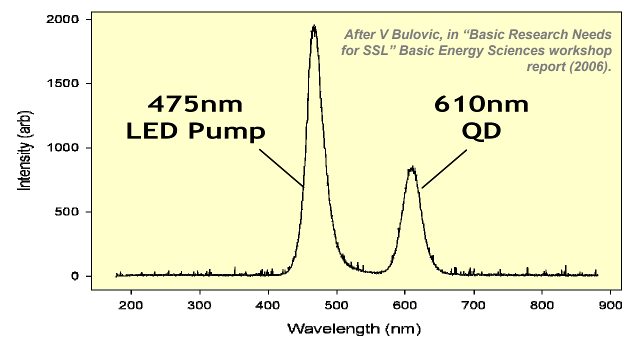


- Dislocation free
- Strain relaxation for compositional freedom
- Electron/hole confinement
- Facet engineering for control of polarization fields
- Waveguiding for lasers

*Nanodots: routes to narrow-linewidth orange-red phosphor*

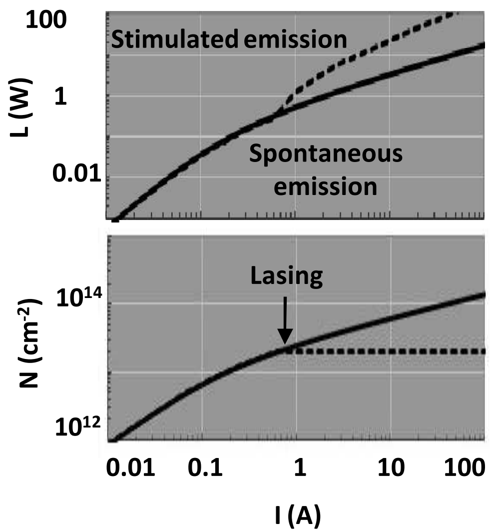



Luminescence of CdS QDs

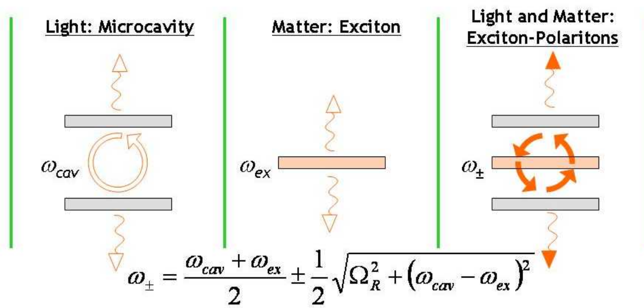


# EFRC Thrust 3: Beyond Spontaneous Emission

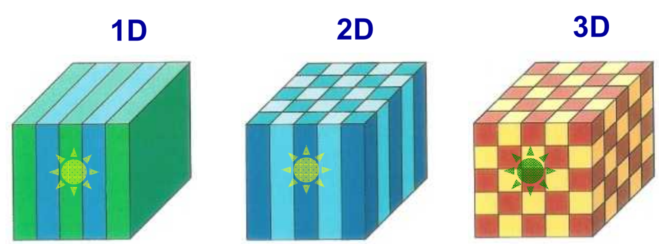
## *Lasers and stimulated emission*




## *Polaritons in subwavelength photonic cavities*

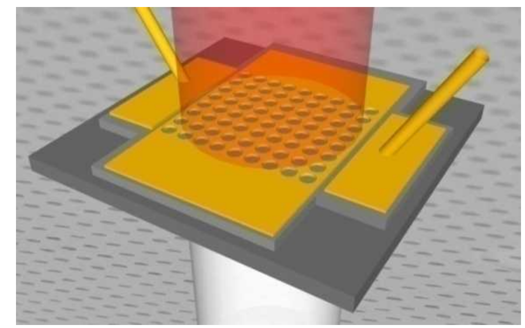



*After A Nurmikko, "Basic Research Needs for SSL" Basic Energy Sciences workshop report (2006).*

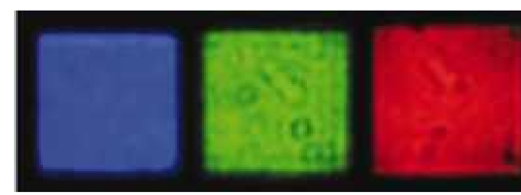



*Photonic crystal nanostructure cavities, courtesy of Art Fischer, Sandia National Labs*

## *Plasmonic intermediaries between excitons and free-space photons*



*Courtesy of Eric Shaner, Sandia National Labs*

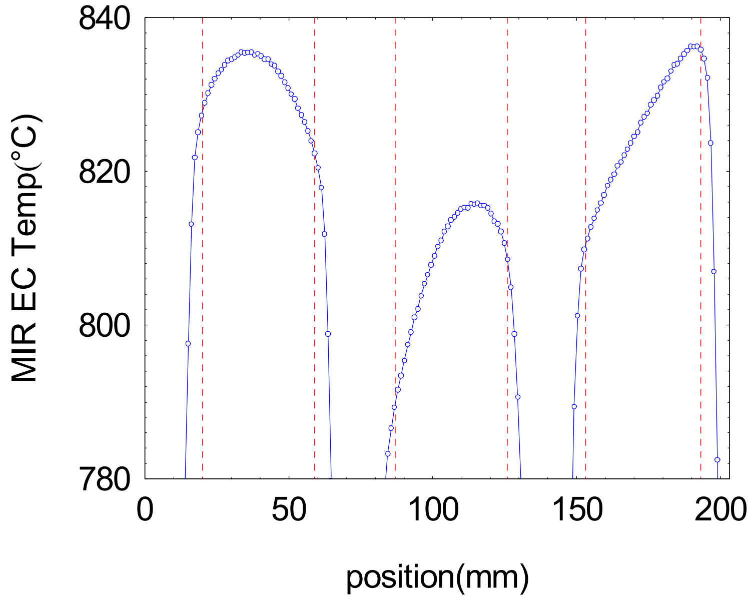


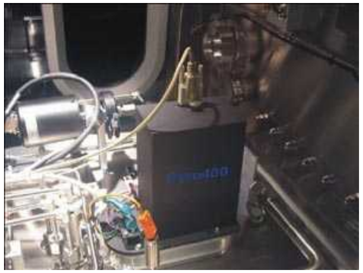
*WL Barnes, et al, "Surface plasmon subwavelength optics," Nature 424, 824 (2003).*

# Improved InGaN Epitaxy Yield with Veeco

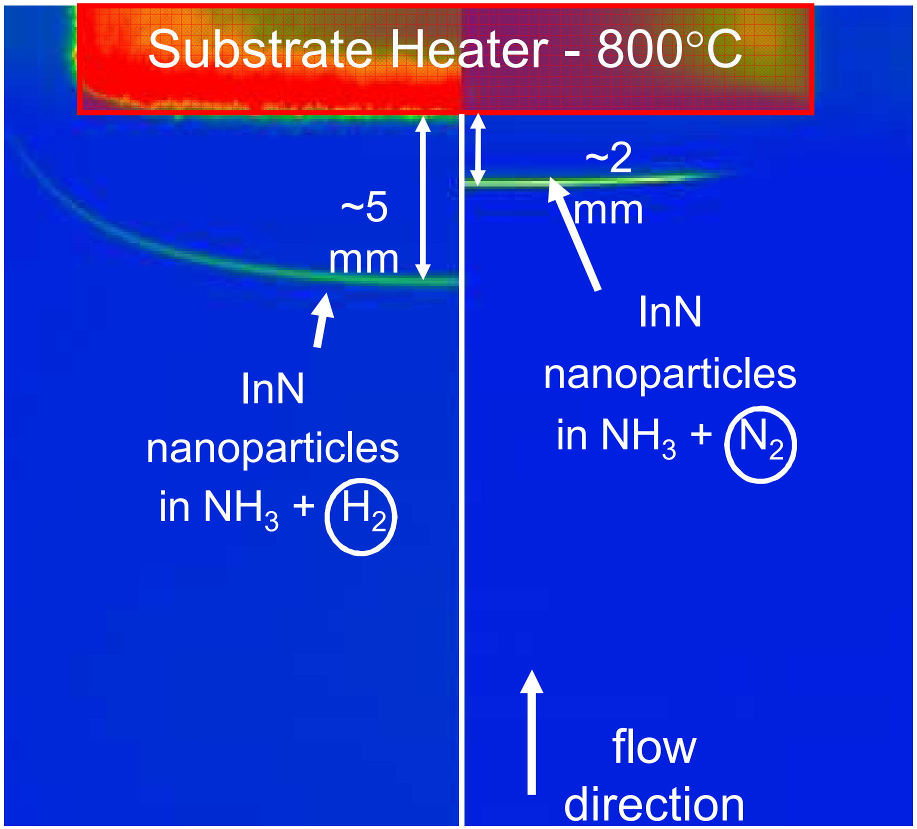
DOE/EERE Manufacturing Initiative for SSL – Randy Creighton

**Spatially-Resolved Emissivity-Correcting Mid-IR Pyrometer**

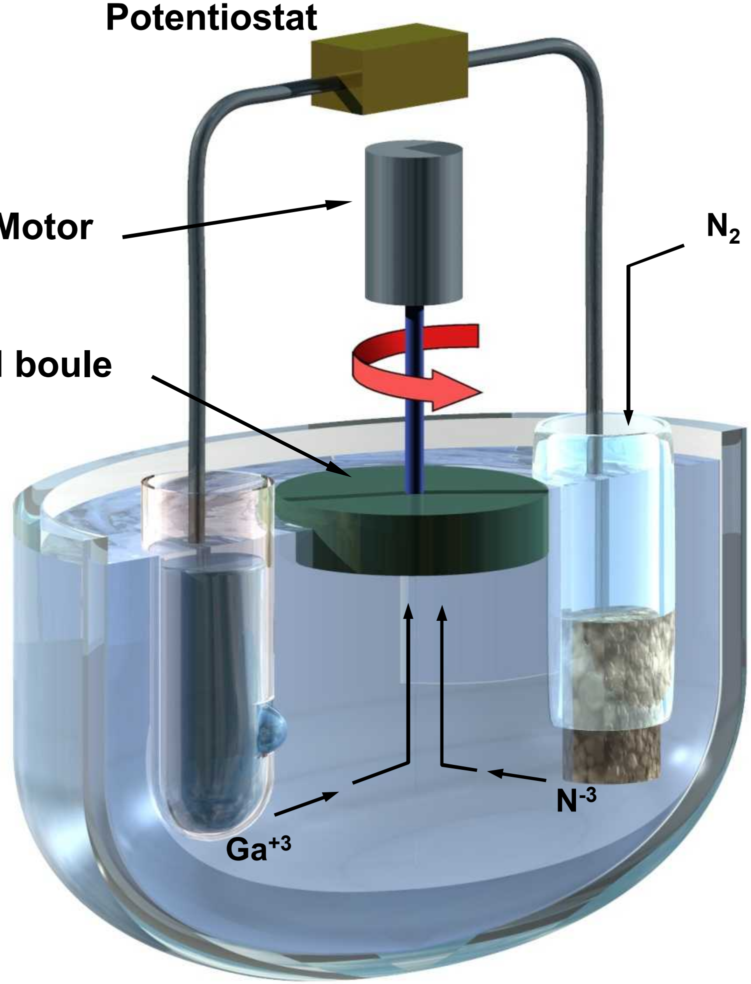


Couple Fluent and Chemkin using Sandia Data and Models



# Electrochemical Solution Growth (ESG): A New Technique for Bulk GaN Growth




450C
1 atm

**Create Ionic Precursors Electrochemically:**

$$2Ga \rightarrow 2Ga^{+3} + 6e^-$$

$$N_2 + 6e^- \rightarrow 2N^{-3}$$

$$Ga + N_2 \rightarrow Ga^{+3} + N^{-3} \rightarrow GaN$$

**Use salt flow to deliver precursors to seed crystal surface**

**Increase growth rate through flux of reactants (increase spin rate)**

***Precursors can be replenished as they are consumed***
***Advantage: Continuous, isothermal or steady-state growth***

***U.S. Patent Issued October 2008***

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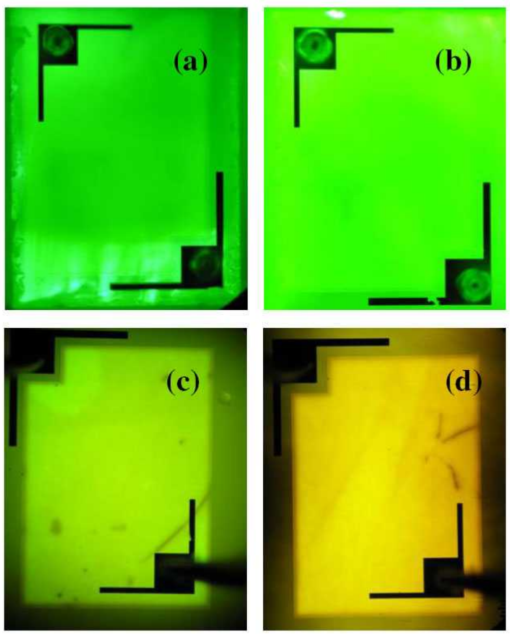
# Higher indium incorporation on semipolar GaN

*Fellows et al., JJAP 47, 7854 (2008).*




$(11\underline{2}2)$

$\lambda$ = 568 nm
EQE = 8.0%

LEDs shown at 1 mA forward bias

Since there is minimal QCSE, there has to be ~ 40% indium concentration in the QW to reach these wavelengths.

**On c-plane GaN, indium is limited to ~20-25%.**

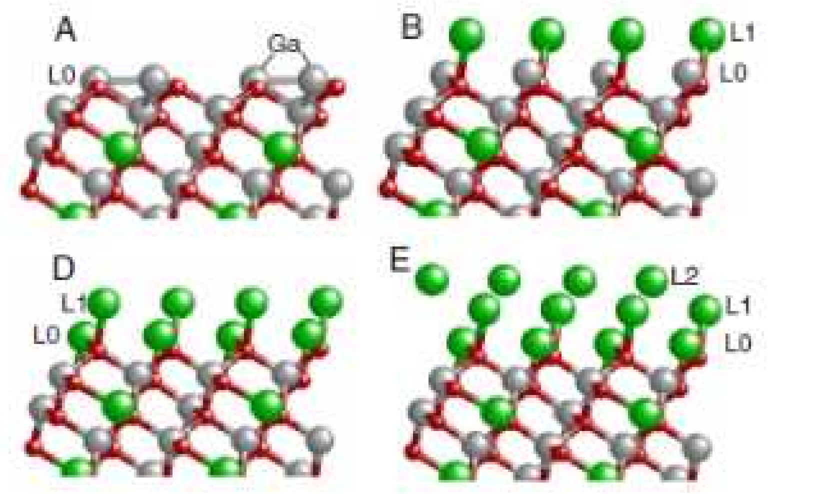


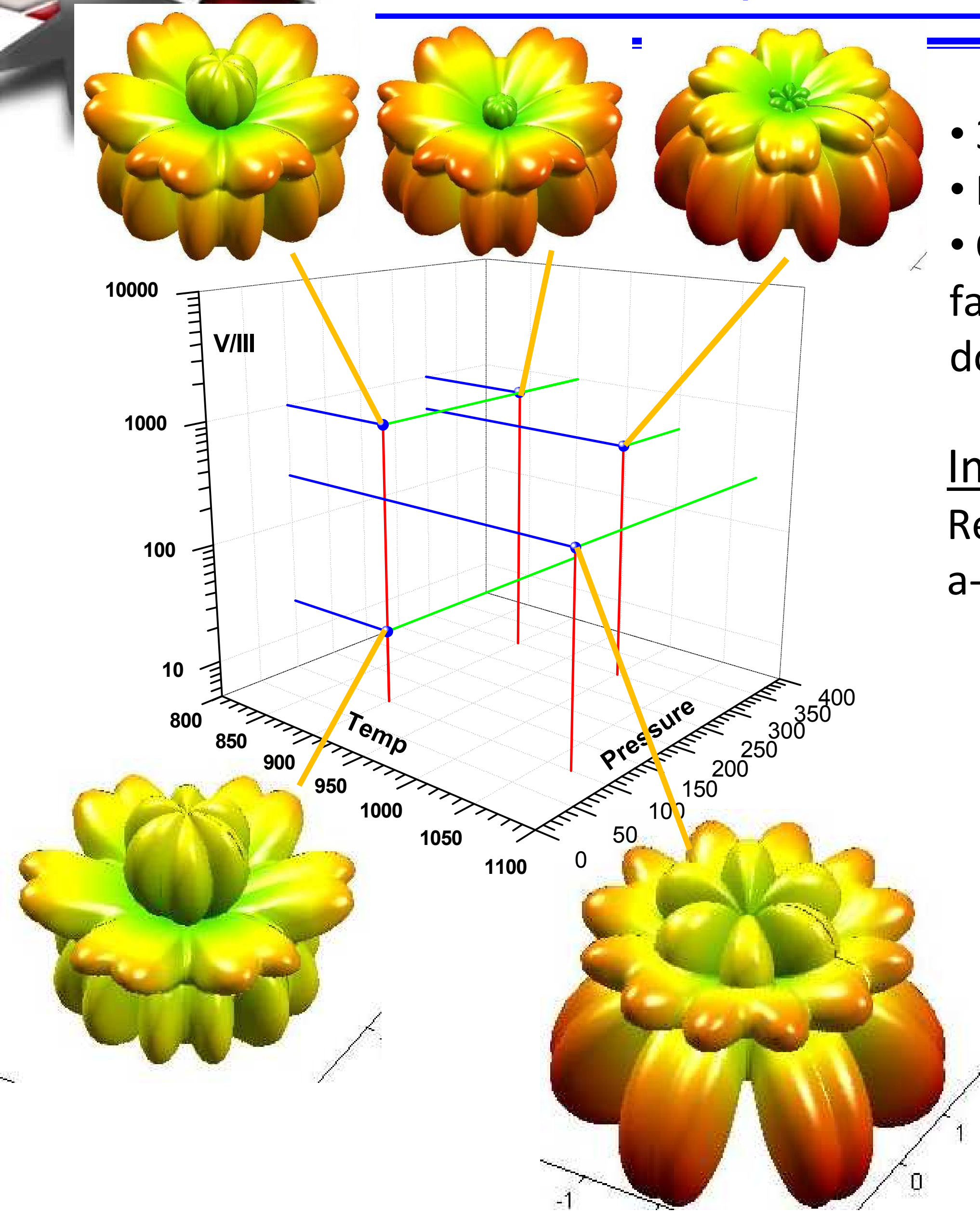

FIG. 3. (Color online) InGaN$(11\underline{2}2)$ surfaces. A, B, D, and E contain successively more In atoms in layers L0, L1, and L2. Indium atoms are large green spheres, Ga atoms are gray, and N atoms are small red spheres.

*J. E. Northrup, Appl. Phys. Lett. 95, 133107 (2009).*

Recent DFT calculations predict greater indium incorporation on GaN (11-22) compared to GaN (10-11) due to reduced strain between the surface incorporated indium atoms.

**Implies that higher indium concentrations can be achieved above the coherency strain limit.**

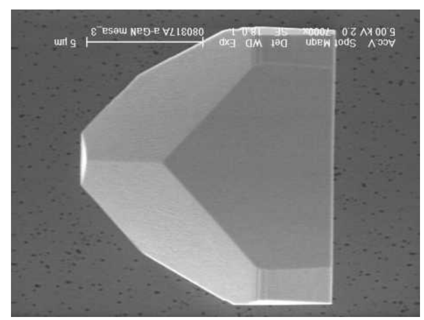
# Kinetics of Semi-Polar GaN Morphology Evolution (Mike Coltrin collaboration with Yale Univ.)

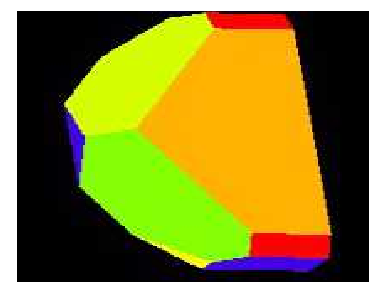



- 3-D v-plots mapped for 5 growth conditions
- Model of convex, a-GaN SAG island shape.
- Observed growth rates of concave facets: facets speed up with increased T and slow down with increasing P, and V/III ratio

## Impact:

Results give insight into planar epitaxy of c-, a-, m-, and (11$\bar{2}$2)-plane GaN





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LUX ET VERITAS

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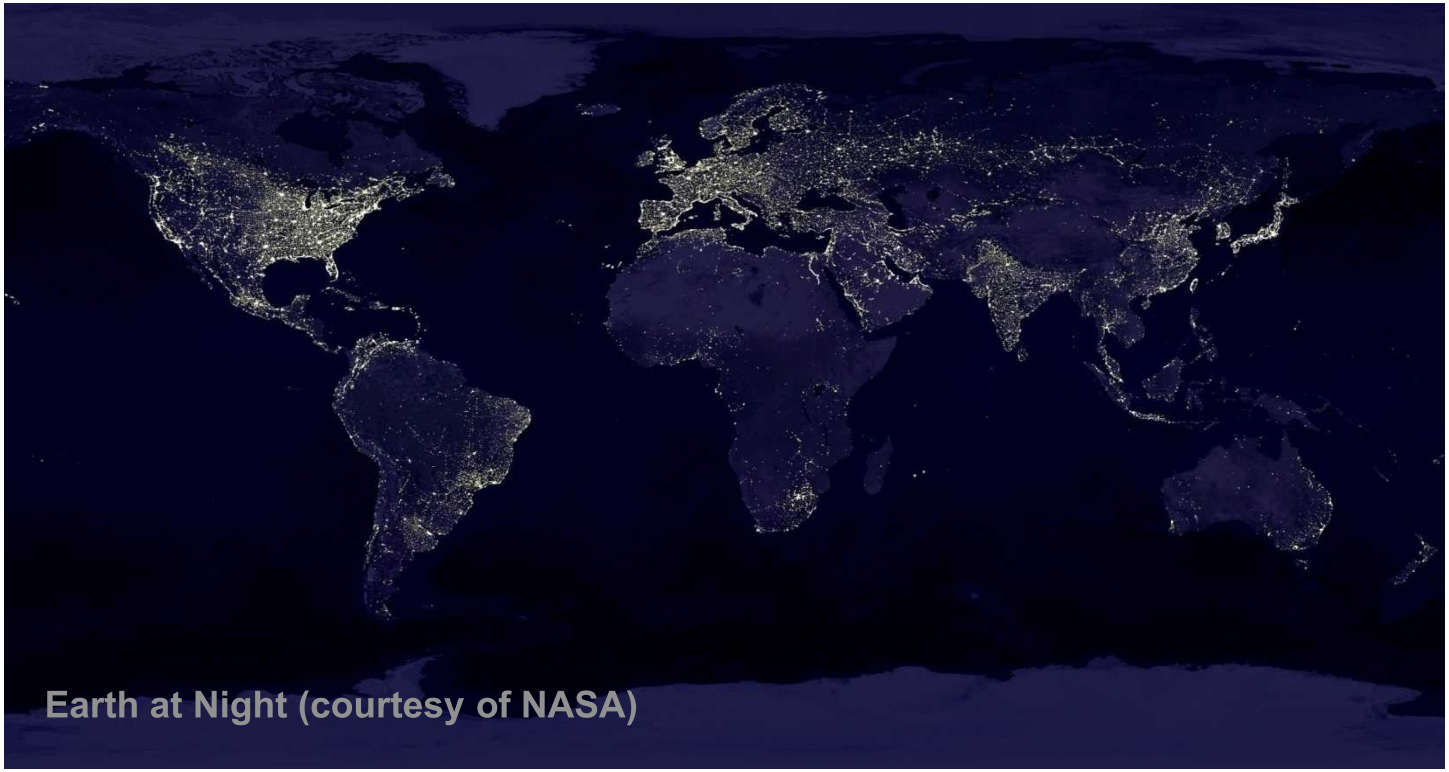
# Lighting the Earth




- 50% Energy Efficient Solid State Lighting could replace all conventional lighting in the next 25 years or so.
- This would result in a 10% reduction in global electricity use.
- Much of this revolution will be enabled by **SSL *research*.**

Thank-you for your attention