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Sandia Microsystems: Impact from Science to Industry

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Physical, Chemical and Nano Sciences Center

Sandia National Laboratories

August 30, 2011

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.

National labs take on big problems for the nation

Sandia's Missions

Nuclear Weapons	Defense Systems & Assessments	International, Homeland, & Nuclear Security	Energy, Climate, & Infrastructure Security

High reliability, high consequence of failure, challenging environments, needing science and technology solutions

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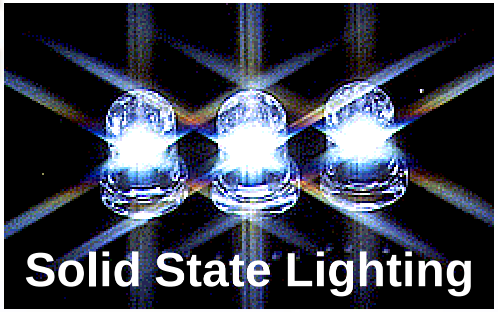
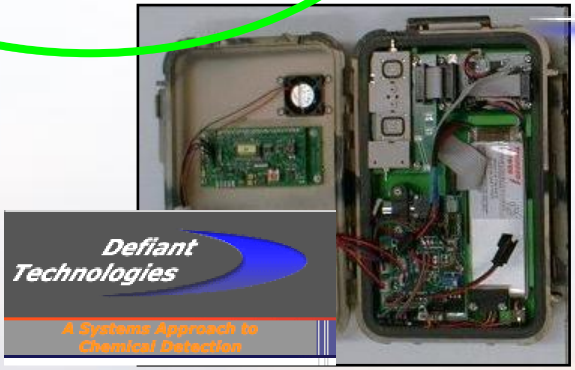
Bring impact through partnerships with industry

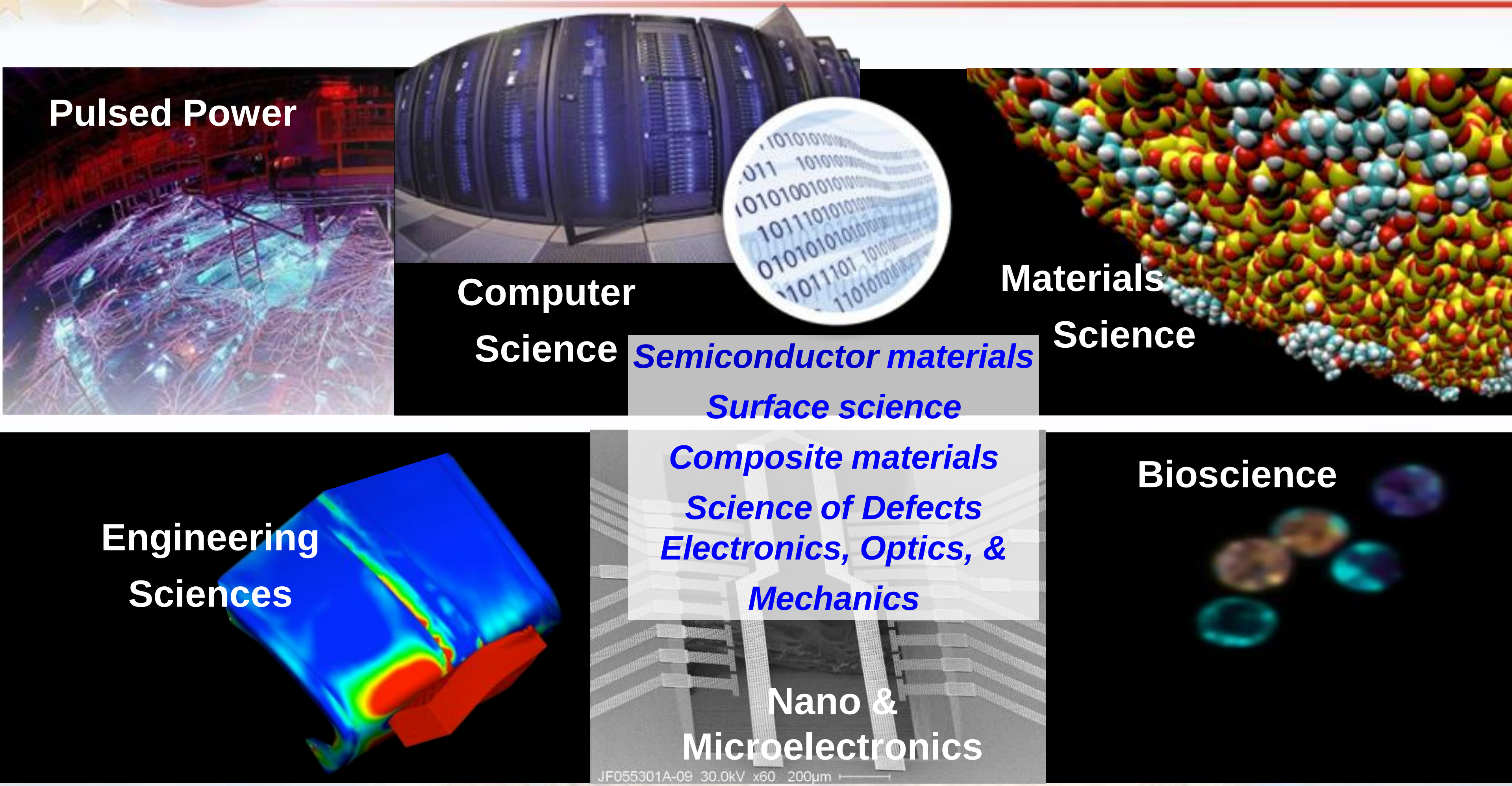




Industry brings products to market, not national labs

National labs shouldn't compete with industry or universities

Sandia has multiple unique strengths that industry partners utilize



Fundamental research and discovery in science and engineering advance our missions

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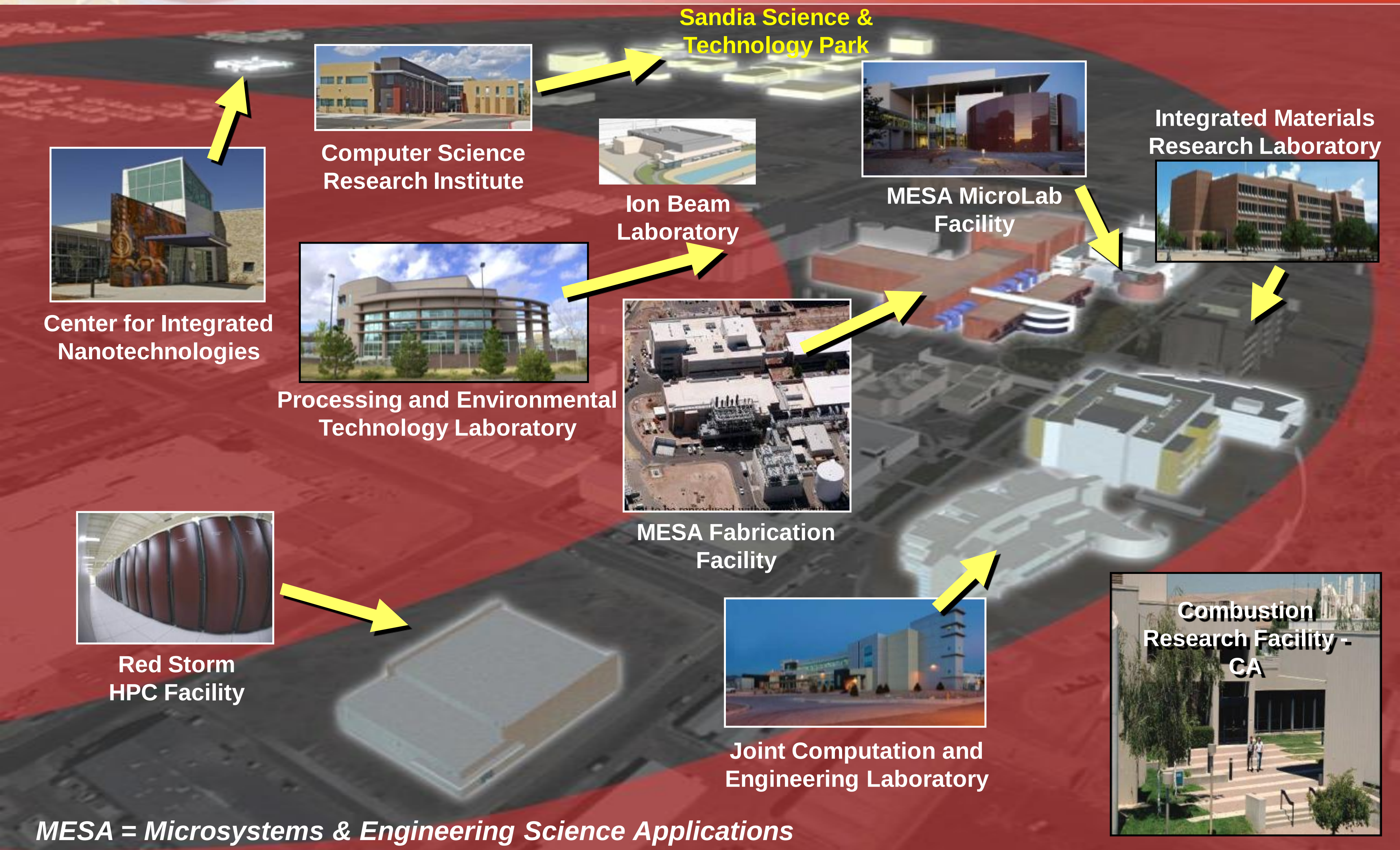
Unique Facilities in the NM Innovation Corridor & Livermore Valley Open Campus



SEMATECH CRADA

SEMATECH and DOE sign a 5 year CRADA (1993)

- materials and process analysis
- equipment modeling and design
- semiconductor process analysis
- equipment benchmarking and engineering
- contamination free manufacturing research
- equipment and software reliability

DEPARTMENT OF ENERGY • UNITED STATES OF AMERICA •

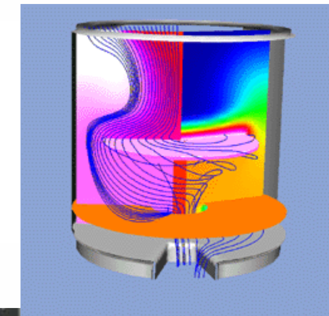
SEMATECH

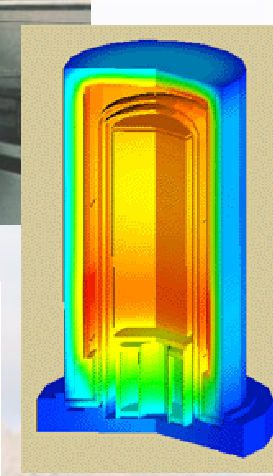
Accelerating the next technology revolution.

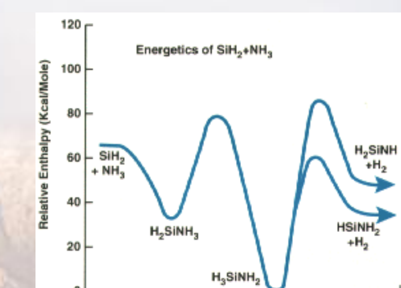
Government Investment in Basic R&D

Office of Basic Energy Sciences

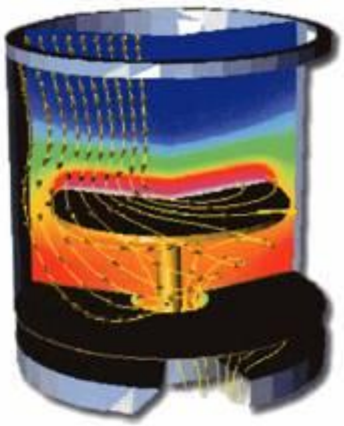
- **Sandia expertise in metal-organic chemical vapor deposition technology**
- **Basic R&D in:**
  - Fundamental materials physics
  - Growth chemistry and reactor physics
  - In-situ monitoring and stress-engineering



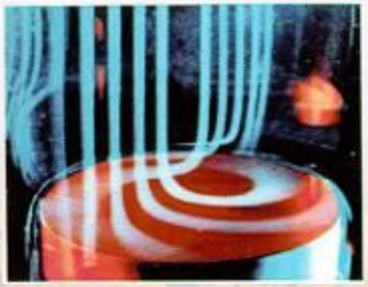




First CRADA with EMCORE



- **EMCORE signs $3.9M CRADA with Sandia (1993).**
- **Apply Sandia expertise for design of production-scale rotating-disk MOCVD reactor**
- **CRADA spans six years.**



emcore

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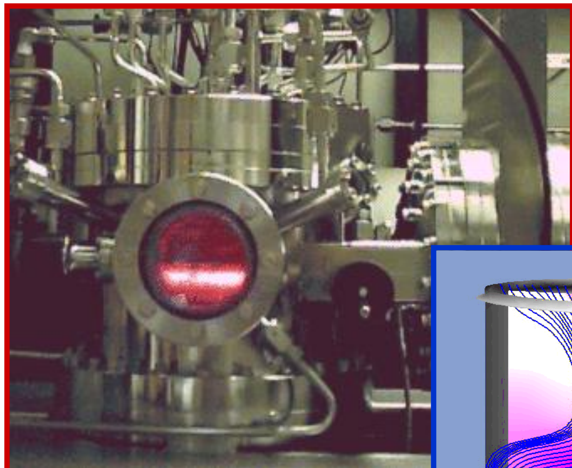
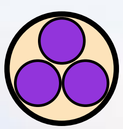
Sandia Helped Emcore Design Next-Generation MOCVD Reactor: ENTERPRISE 400

"A sterling example of the benefits of such partnerships. In business, time is money, and Sandia's responsiveness has helped us greatly in our market."

Norm Schumacher, Pres., Emcore, ca. 2001

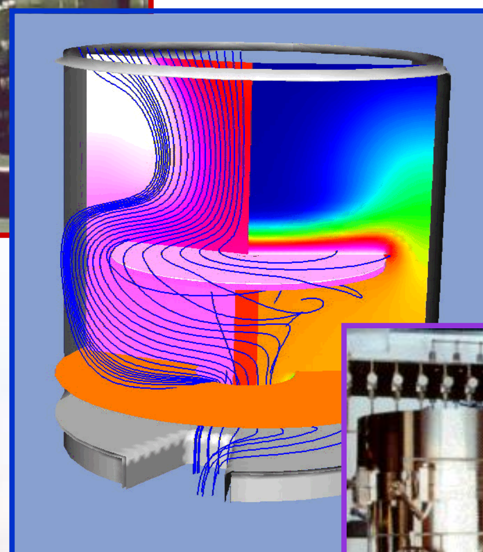


Emcore Discovery 125

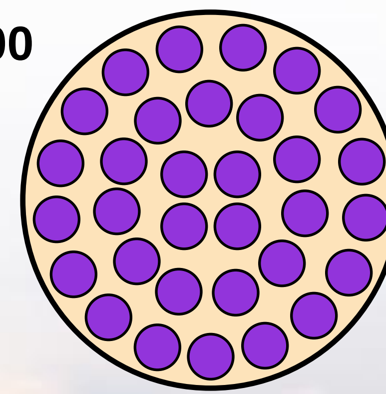


3 two-inch wafers

(Earlier reactor)



Emcore Enterprise 400



32 two-inch wafers

(New reactor design)

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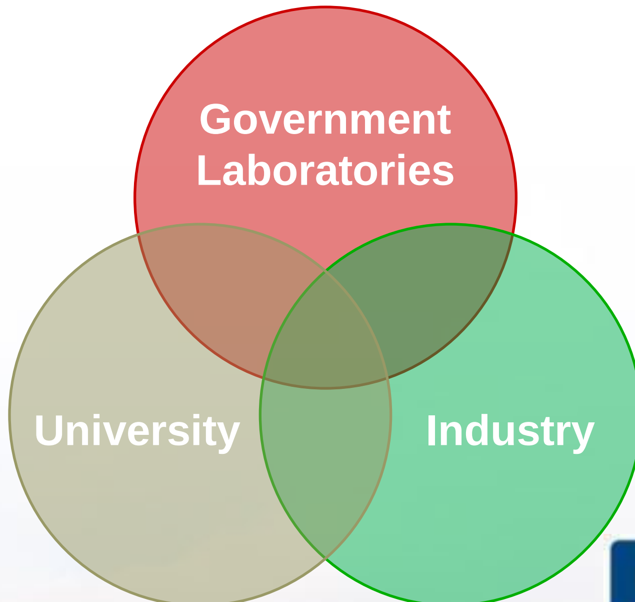
Big problems take multiple partners

Accelerating Innovation



The University of New Mexico

Harvey Mudd College 50 Years

University of Wisconsin System

Harvard

Texas

University of California

Yale

University of Notre Dame

Rice University

Rensselaer Polytechnic Institute 1824

清華大学 Tsinghua University

NUS National University of Singapore

CAERC

AIST National Institute of Advanced Industrial Science and Technology (AIST)

Lockheed Martin

Corning

P&G

Philips

intel

Goodyear

IBM

hp invent

ExxonMobil Taking on the world's toughest energy challenges.

SES Stirling Energy Systems PURE POWER MADE SIMPLE

emcore empower with light

GM

Cummins

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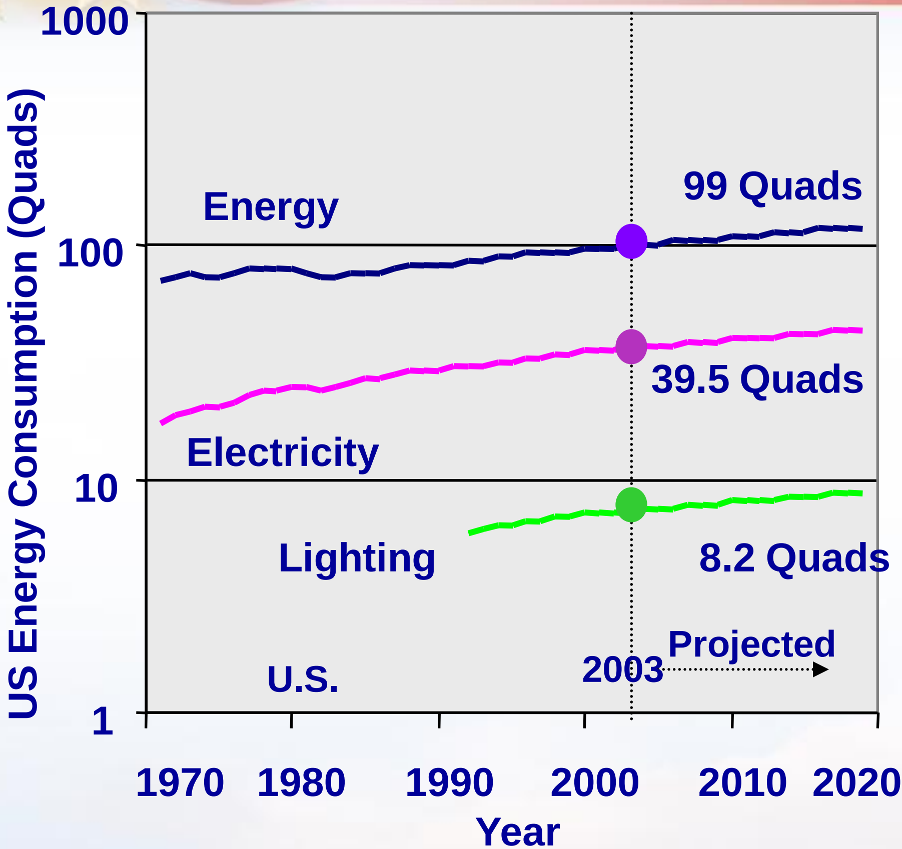
Energy security is a big problem

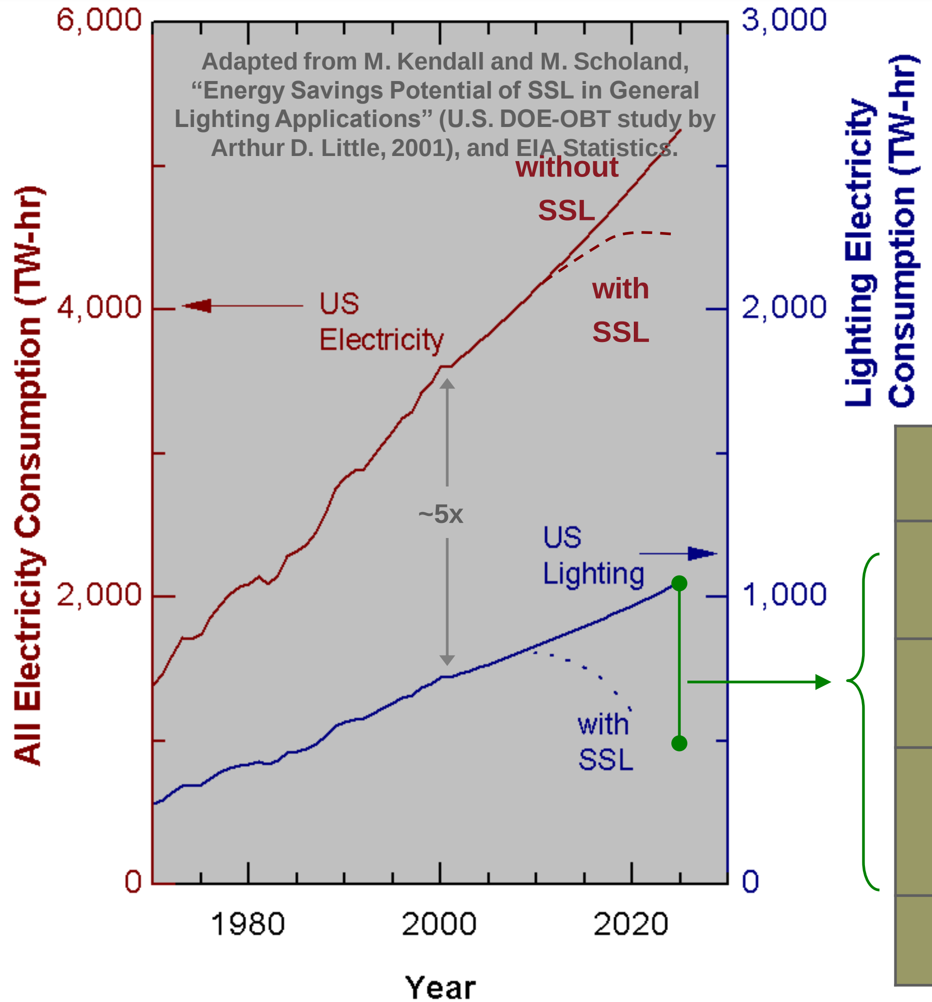


Efficiencies of energy technologies in buildings:

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

- ~22% of electricity consumption is for general illumination
- Lighting is a highly attractive target for reducing energy consumption!

50% efficient SSL delivers a huge energy saving

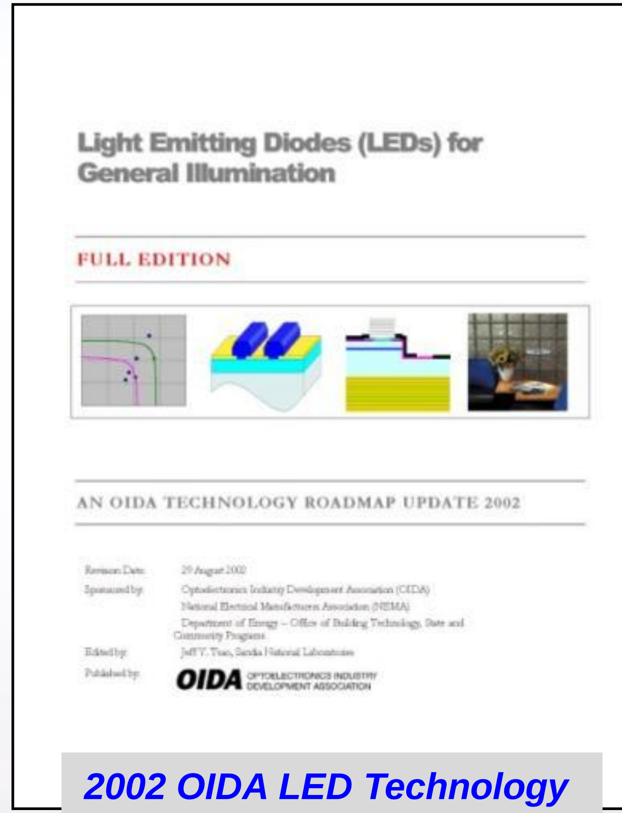


- SSL has the potential, by 2025, to:
  - decrease electricity consumed by lighting by >50%
  - decrease total electricity consumption by >10%

Projected Year 2025 Savings	US	World
Electricity use at site (billion kWh)	525/ year	1,800/ year
Money spent on Electricity	$35B/ year	$120B /year
Electricity generating capacity (GW)	75	~260
Carbon emissions (Mtons)	75	~260

Significant Industrial Collaborations Began in 2000 and Continue Today

- Philips Lumileds (originally with HP)
- General Electric
- Cabot Superior Micropowders
- Dow Corning
- Veeco
- Emcore
- Cree



2002 OIDA LED Technology Roadmap (edited by SNL)

Sandia hosted & edited DOE/OIDA SSL Technology Roadmap Workshops in 2000 and 2002, and provided technical background information to congress

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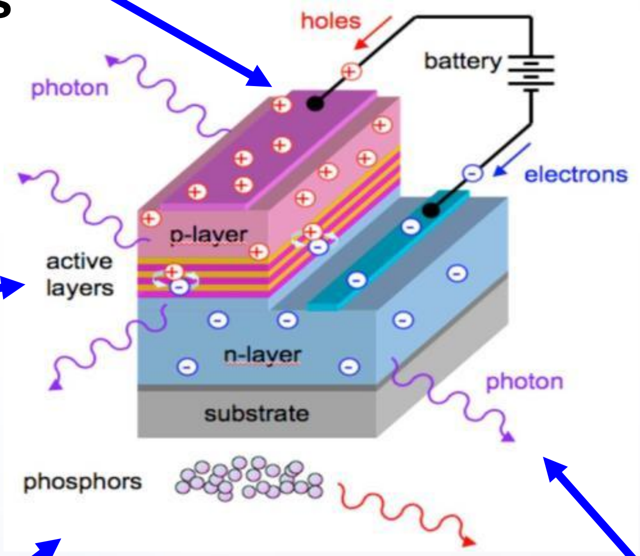
Science and technology challenges

Injection & transport of charge carriers

Radiative & non-radiative recombination



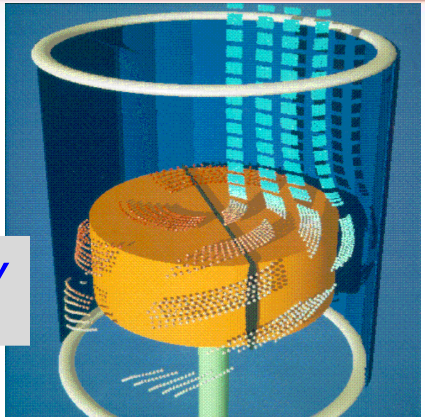
Color conversion & multi-color mixing

Light extraction

Initial solutions to science and technology challenges: material deposition

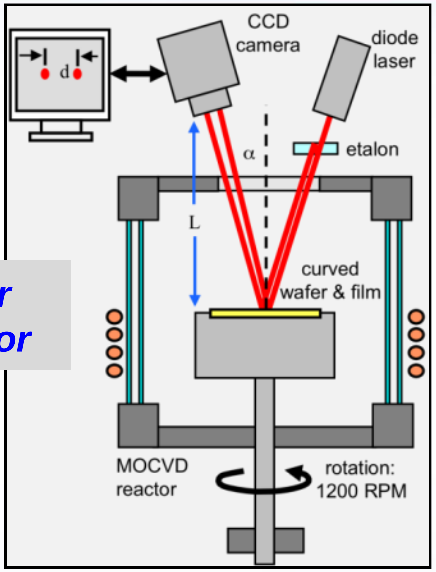
Chemical Vapor Deposition Sciences

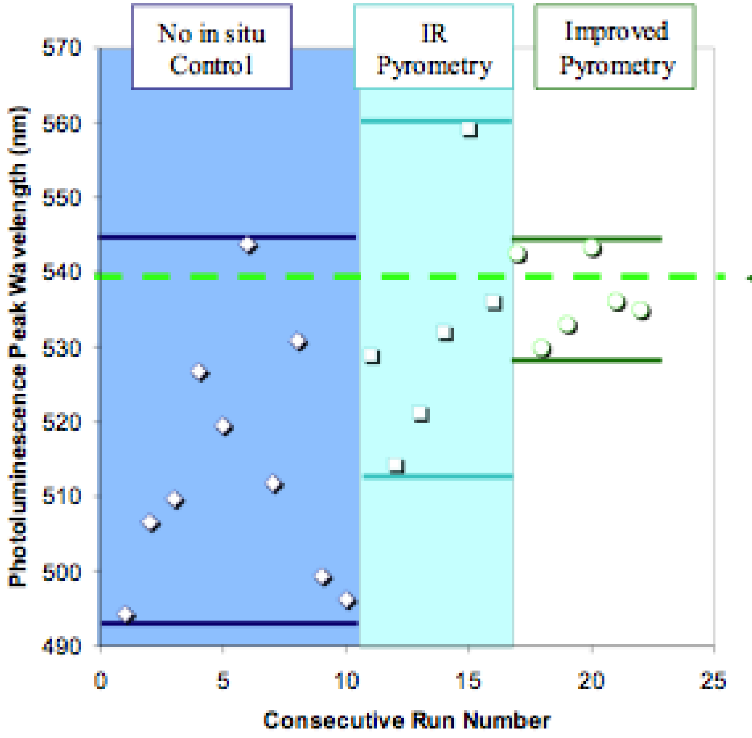
Modeling of chemically reacting flows



Advanced Growth & Science of Epitaxy

In-situ wafer stress monitor





Emissivity-correcting pyrometer increases MOCVD temperature control, dramatically reducing run-to-run wavelength variations

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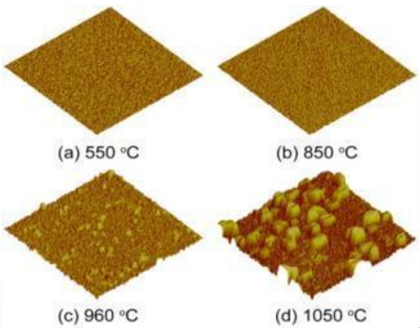
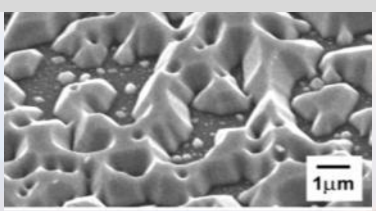
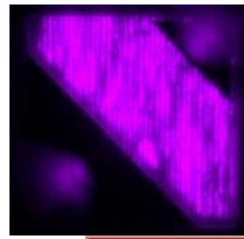
Developed chemical & mechanistic understanding, theory, and new synthesis methods

Understanding and Control of Material Defects

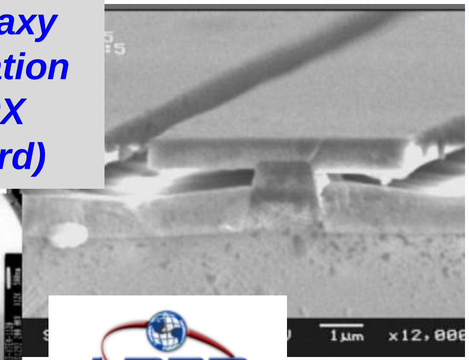


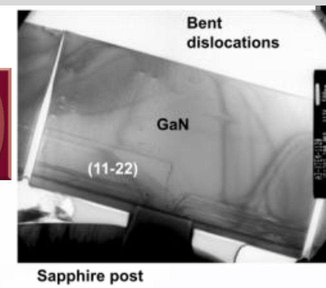
Controlled GaN growth nucleation reduces defect densities and strain relaxation

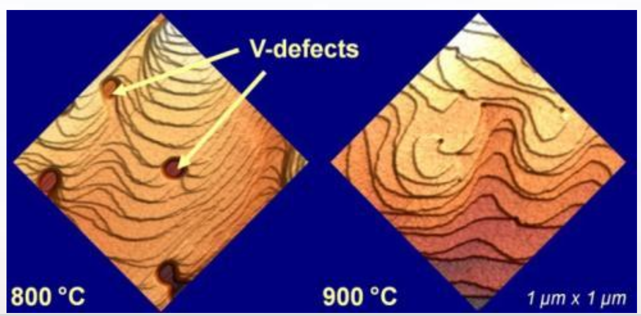




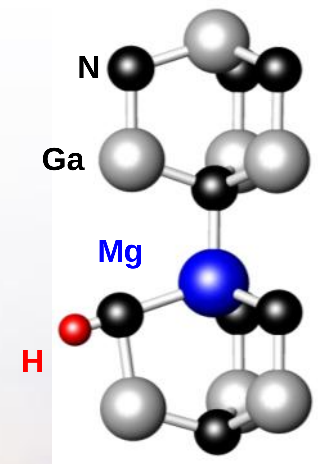
Cantilever Epitaxy reduces dislocation densities 100X (R&D 100 Award)







Extended and point defect dependence on growth temperature



DFT calculations of defect energies

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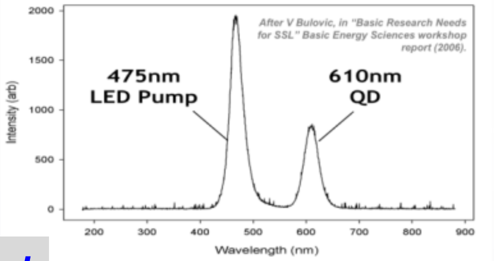
Science and technology challenges: color conversion

Luminescence of CdS QDs



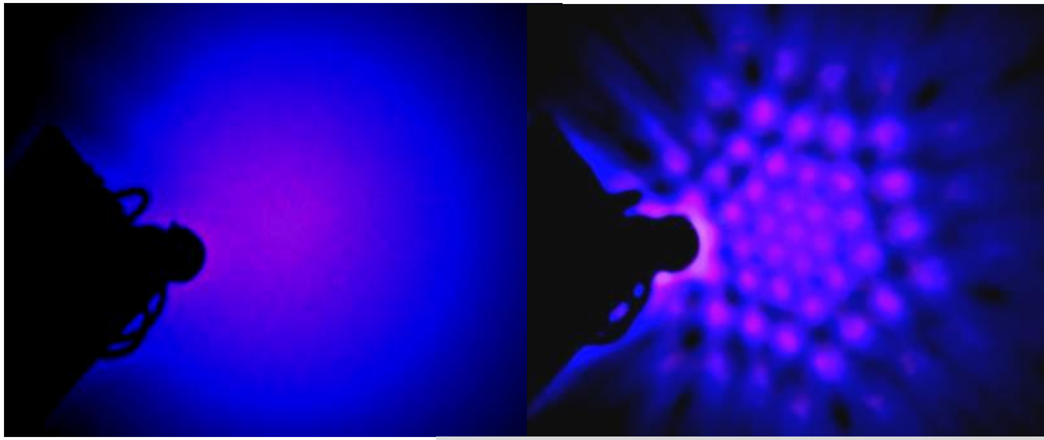
Need new phosphors:

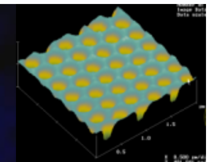
- Fluorescent lighting phosphors are *unsuitable for SSL*
- Efficiency improvements, *especially red*
- Fast photoluminescence lifetimes
- High-T operation
- Low cost
- Non-toxic
- Compatibility with encapsulants
- Long lived under high UV flux

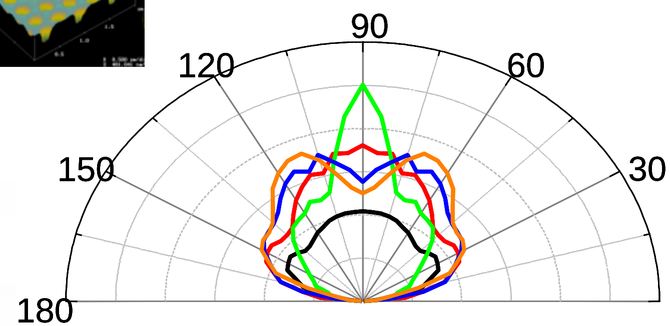
Quantum dots as an engineered alternative to conventional phosphor materials

Improving extraction efficiency and light directionality

Lumileds, Sandia, and UNM (Wierer et. Al., APL 84, 3885 (2004)

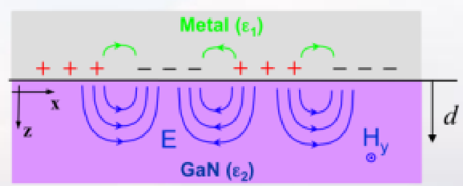


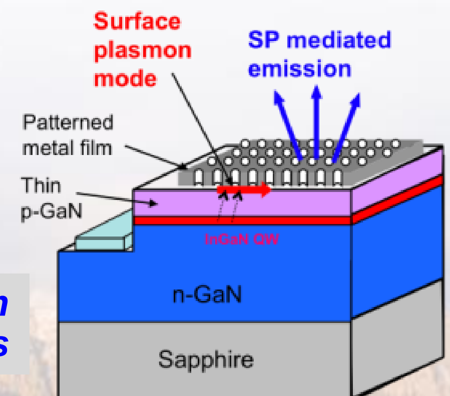




Photonic crystal LEDs exhibit directionality and 50% higher external quantum efficiency

New concepts





Surface plasmon mediated emission from InGaN LEDs using patterned metal films

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LEDs Are Already Superior for Monochromatic Applications

MGM Grand's Teatro

Providence Performing Arts Center

Programmable Lights Ben Franklin Bridge, Philadelphia (Color Kinetics)

LED Flash Camera Phone (Motorola E815)

Rear Combination Lamp (LumiLeds)

LED Backlit LCD Display (Sony Qualia)

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Replacing conventional lighting for general illumination is a greater challenge

Cree LRP-38 Replacement Lamp

Philips 60W Incandescent Replacement

Although there is initial commercialization, important science questions remain and so the partnerships evolve and mature

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Solid state lighting science is a new DOE energy frontier research center (EFRC)

SSLS EFRC
SOLID-STATE LIGHTING SCIENCE
ENERGY FRONTIER RESEARCH CENTER

Research:

- Investigate conversion of electricity to light using radically new designs: nanowires, QDs, hybrid architectures, sub-wavelength structures
- Understand and eliminate defects in SSL semiconductor materials that presently limit the energy efficiency

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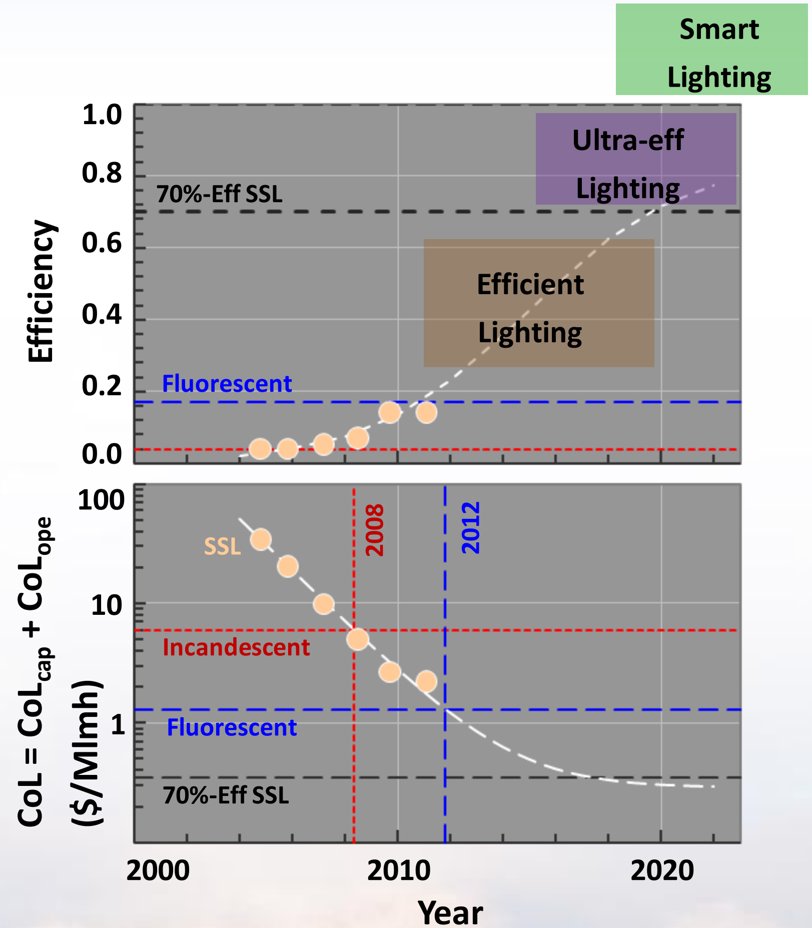
Challenges for next-generation solid state lighting

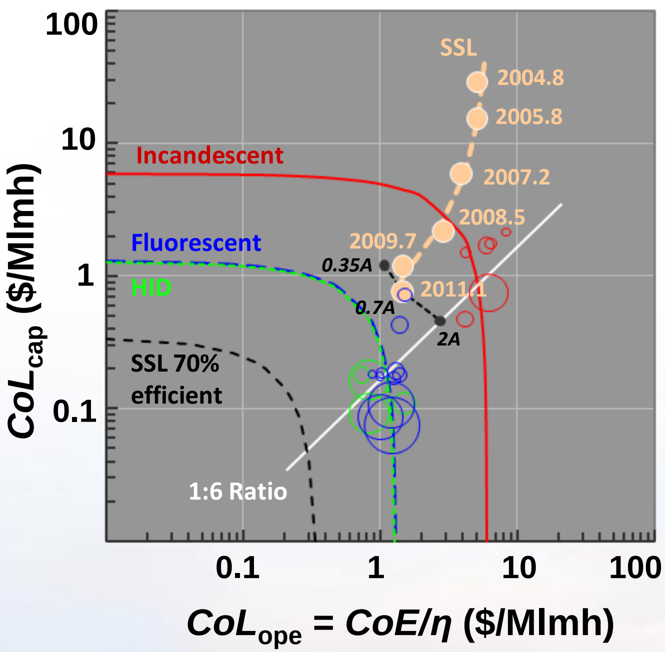
<u>***SSL technology***</u>

- ***Will soon "beat" traditional lighting***
- ***Opportunity for higher risk challenges that take SSL well beyond traditional lighting:***
  - *>70% light production efficiency (ultra-efficient lighting)*
  - *>??% light use efficiencies (smart lighting)*

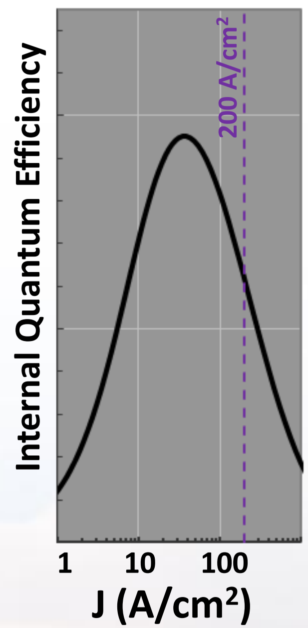


Fundamental experiments and theory to understand efficiency droop

High injected current densities are one route to lower capital cost of light,



if not for efficiency droop,



a phenomenon that we don't yet understand

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

2.8V

0.6Ω

ε_{Joule} Joule efficiency (resistive losses)

Injection efficiency (carrier overshoot and escape)

Shockley-Read-Hall (defect-mediated)

Spontaneous Emission

Auger-like

ε_{IQE} Internal quantum efficiency

Extraction efficiency (photon trapping and absorption)

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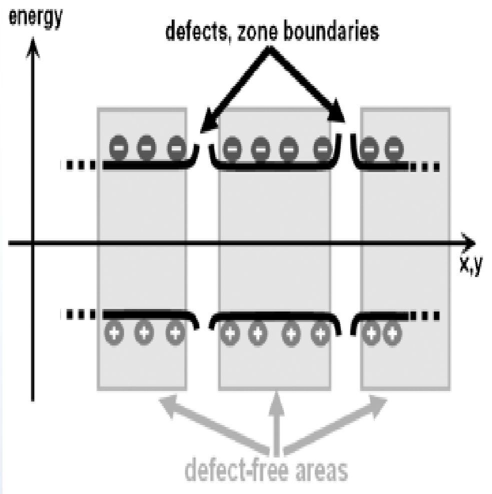
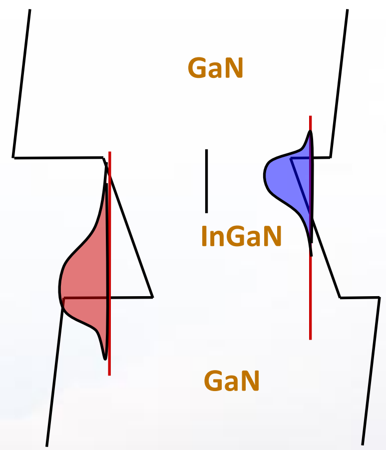
Key Challenges: Treating Inhomogeneous Distributions

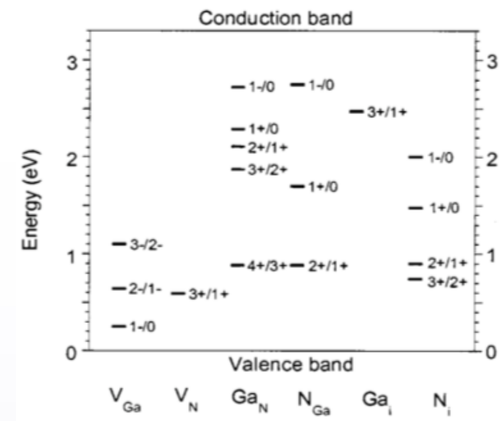
Distribution of bandgaps and defects in xy-plane



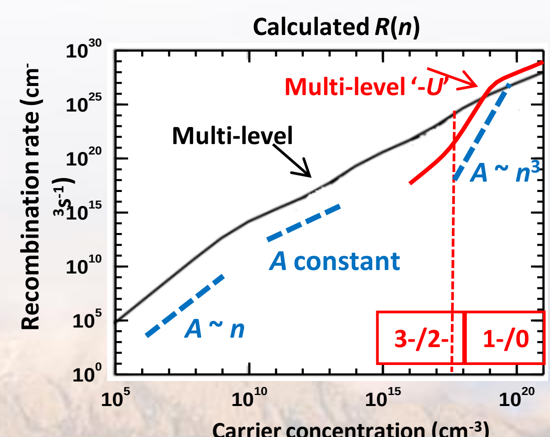
Distribution of polarization fields and carriers along z-axis



Distribution of deep-levels over charge states

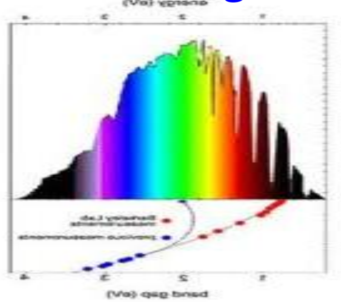


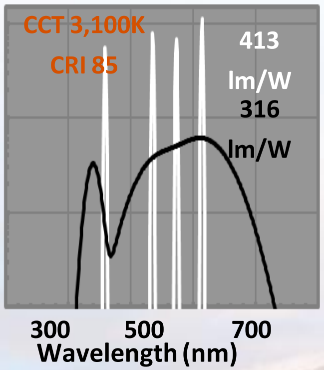
Limpijumnong and Van de Walle, PRB 2004.



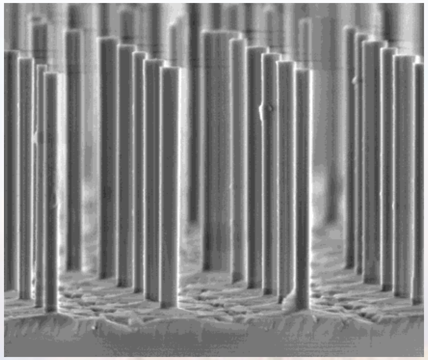
Beyond 2D: 1D Nanowire Synthesis, Properties, Architectures

High InGaN compositions needed to span the desired SSL wavelengths

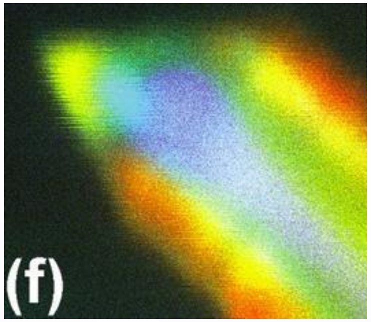


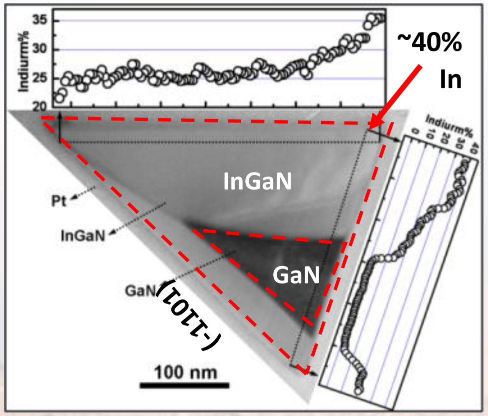


High aspect ratio enables strain accommodation

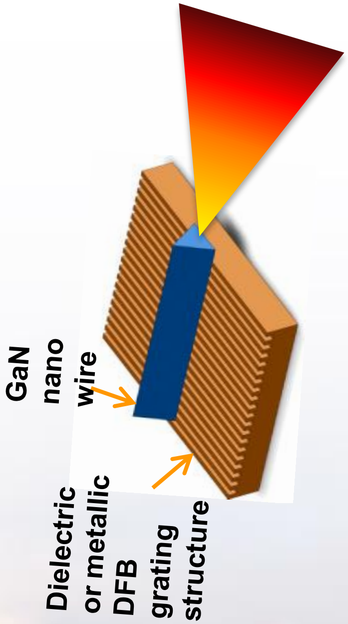


Measurements verify 40% InGaN, with anisotropies



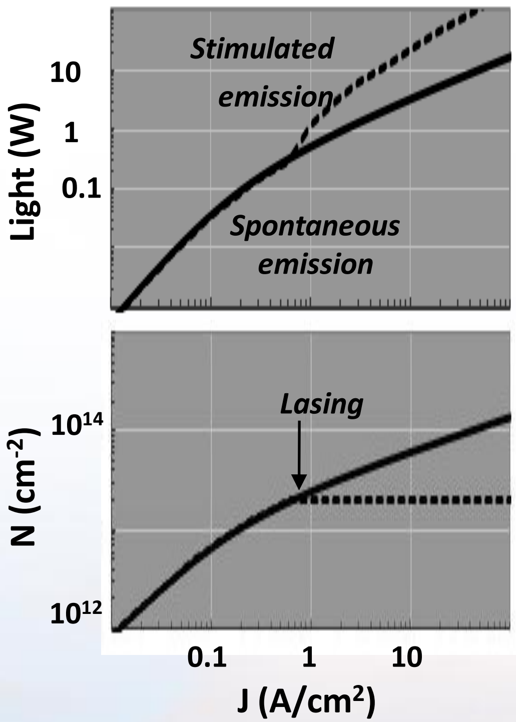


Future work: InGaN nanowire lasing!

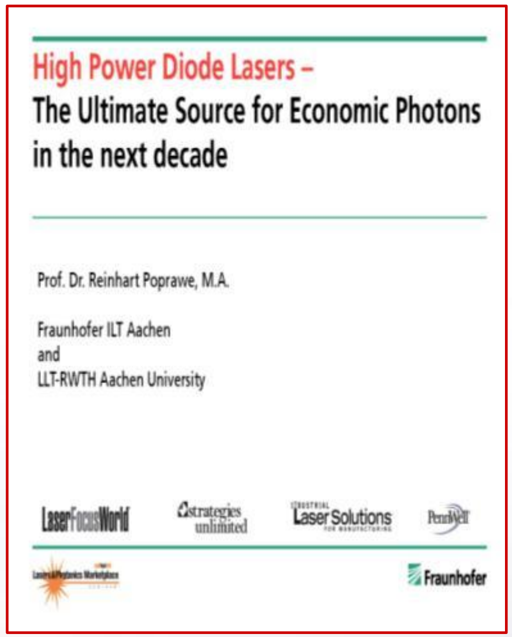


Novel emitter architectures capable of >70% efficiency at >200A/cm² (e.g., lasers)

<u>*Stimulated emission clamps carrier densities*</u>



<u>*High current density enables cheap photons*</u>



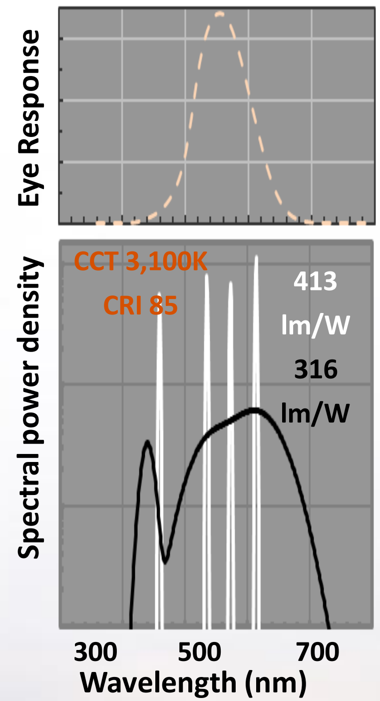
High Power Diode Lasers – The Ultimate Source for Economic Photons in the next decade

Prof. Dr. Reinhart Poprawe, M.A.

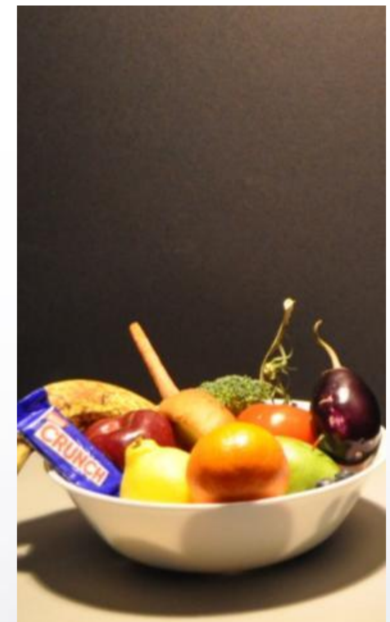
Fraunhofer ILT Aachen
and
LLT-RWTH Aachen University

LaserFocusWorld
strategies unlimited
Laser Solutions
PennWell
Fraunhofer

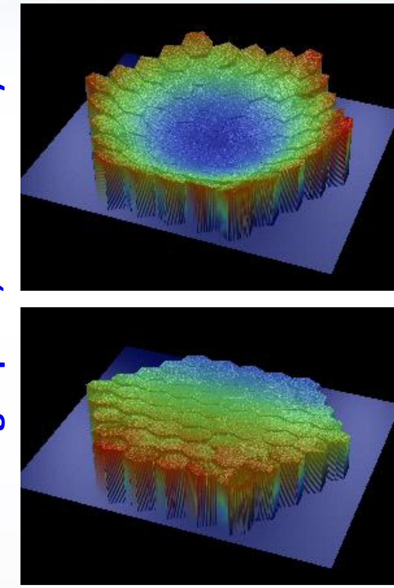
<u>*Narrow linewidths give high LER*</u>



<u>*without sacrificing color quality*</u>



Bringing luminaire functionality to the chip



Piston-tip-tilt mirror array (courtesy of Olga Spahn, Sandia Labs)

Theatre luminaire (expensive)

- Rotates, tilts, focuses, changes chromaticity, digitally controlled
- Hemispherical array gives the ultimate control over the illumination of a scene, but can only afford a few

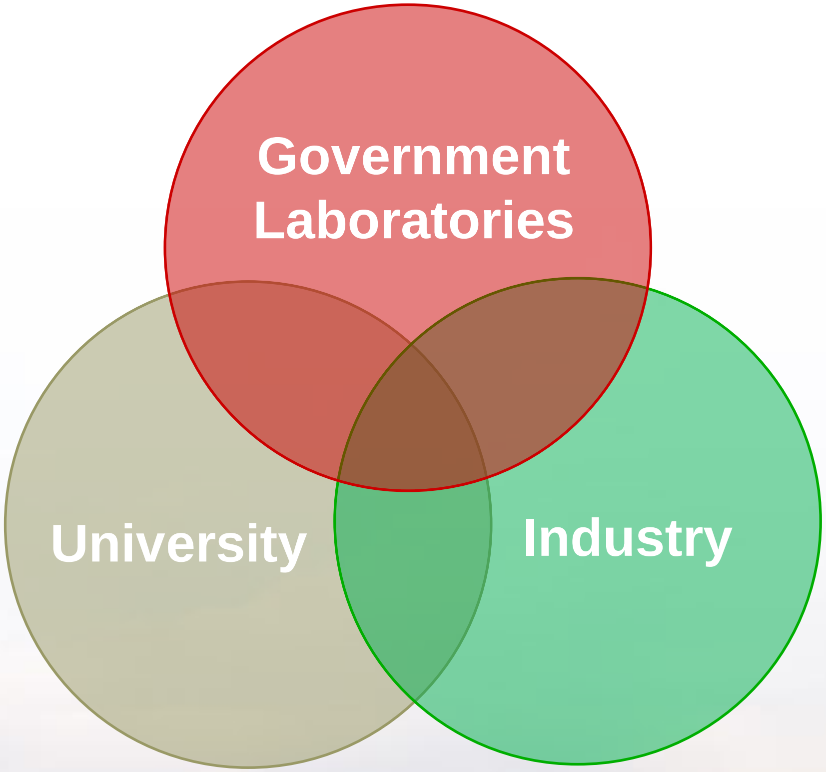
Microsystem luminaire (inexpensive)

- Same functionality as theatre luminaire, but fractionated and ubiquitous
- Opportunity for much higher efficiency and productivity of light use

Challenges

- Luminaire itself
- Integration of luminaire with light sources
- Heat sinking
- Color mixing

Investments in microsystems partnerships will create the next revolution in lighting and reduce energy consumption



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