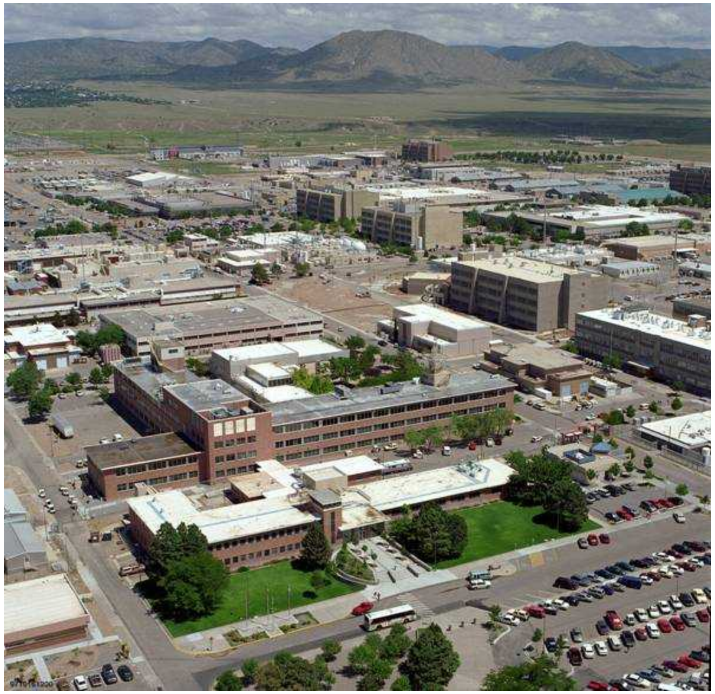
SAND2008-1831P

Sandia's National Institute for Nano-Engineering and Solid State Lighting Programs



Sandia National Labs,
Albuquerque, New Mexico site

Mary H. Crawford
Semiconductor Material and Device Sciences Dept.
Sandia National Labs, Albuquerque, NM

- Introduction to Sandia National Labs
- National Institute for Nano-Engineering
- Sandia Solid State Lighting Programs

RPI, March 19, 2008

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

NNSA National Nuclear Security Administration

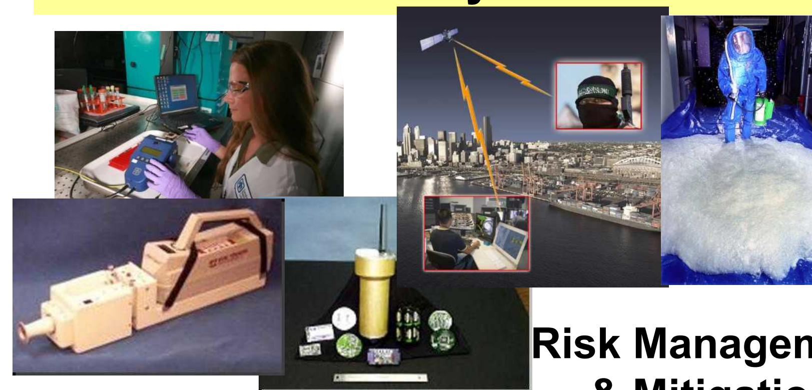
Sandia National Laboratories

Sandia's Primary Mission Areas

Nuclear Weapons

Safe, Secure, Reliable Weapons

Homeland Security and Defense



Detection

Risk Management & Mitigation

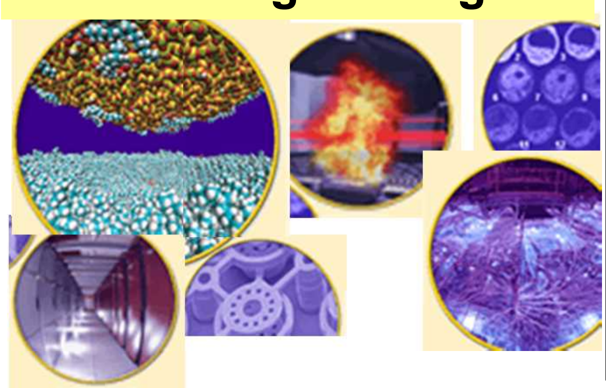
Energy & Infrastructure

Nuclear Energy

Fuel & Water

Global Security

Science, Technology and Engineering



Defense Systems & Assessments

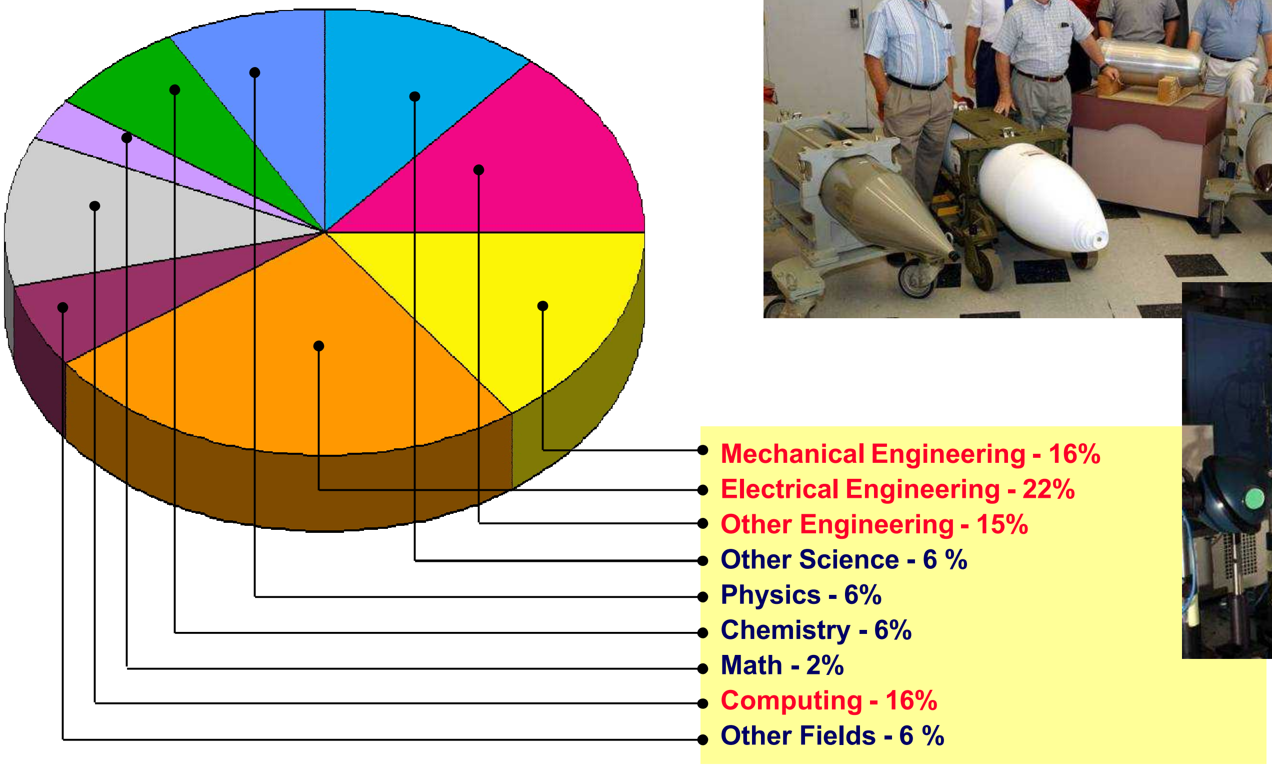
Military Systems

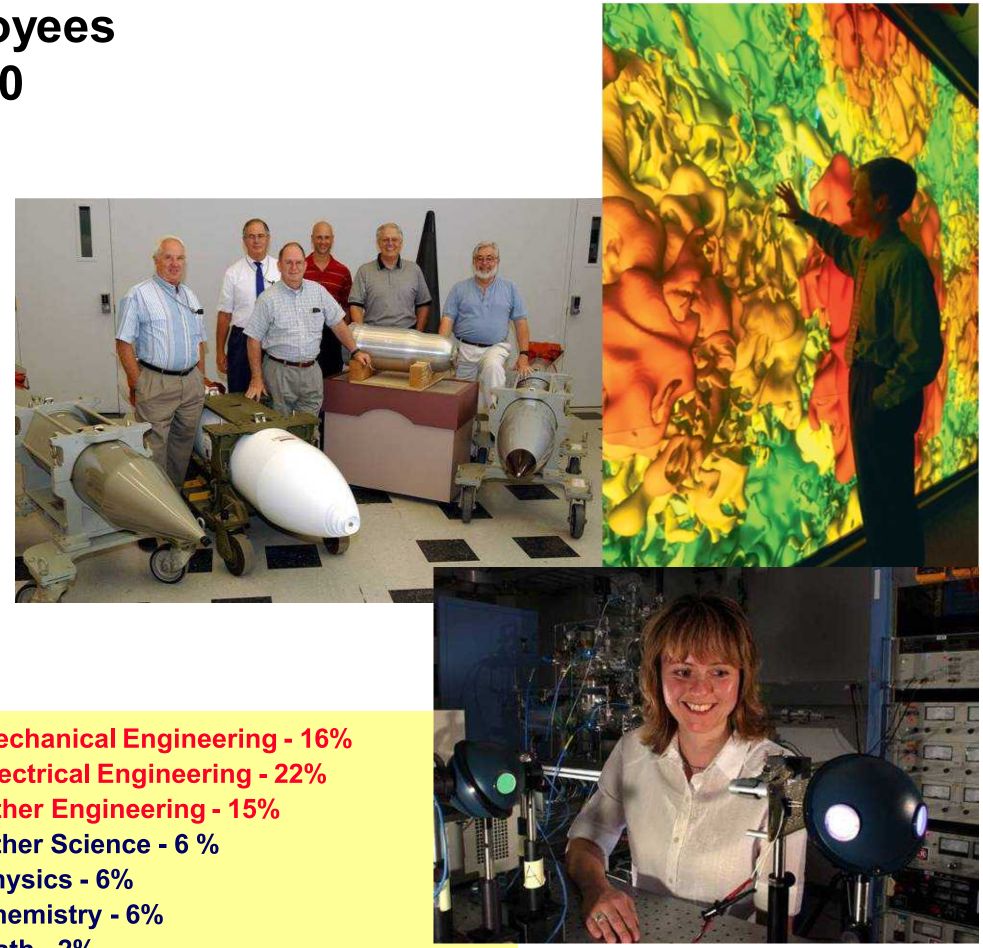
Surveillance

Sandia National Laboratories

Sandia Workforce

- More than 8,600 full-time employees
- More than 1,500 PhDs and 2,700 MS/MAs
- 2,200 on-site contractors
- $2.33 billion FY06 total budget





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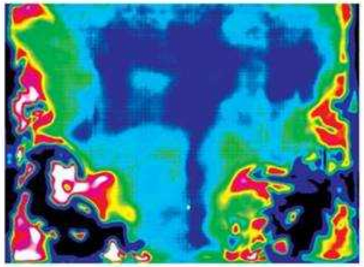
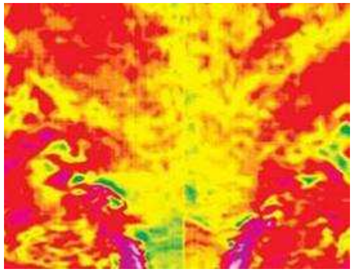
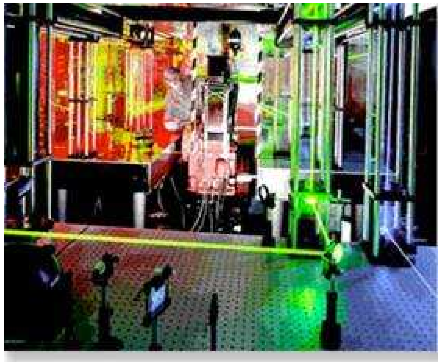
Energy Efficiency Programs

Reducing Demand on our Energy Resources



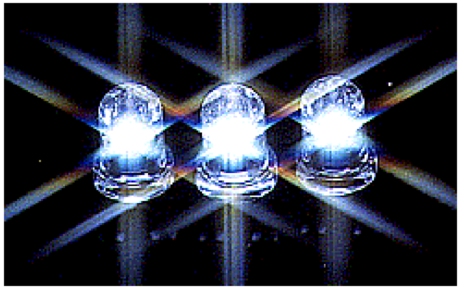


…exploring hydrogen-blended hydrocarbon fuels



…pioneering work in the use of lasers for characterizing combustion events

…supporting national efforts in solid state lighting



…developing technology to improve efficiency and reduce the environmental impact of automobile and truck engines

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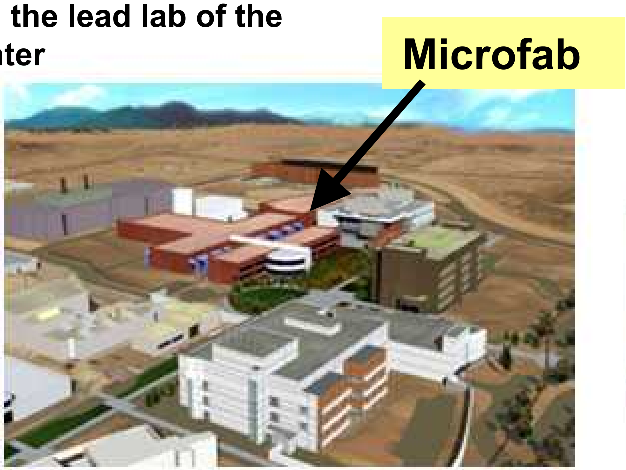
Two New Research Facilities and National Lab Center for SSL R&D

DOE Sec. Bodman announced the National Center for SSL R&D

Sandia has been designated the lead lab of the National Center

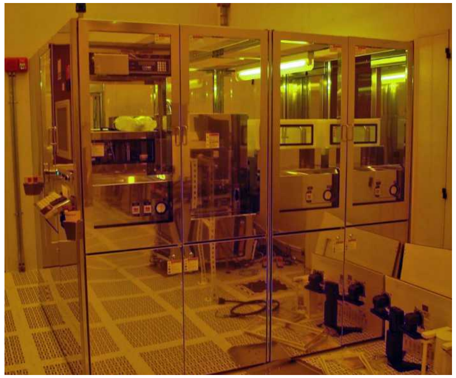


Microsystems and Engineering Sciences Applications (MESA)

CINT Core Facility in Albuquerque

CINT Gateway to Los Alamos

Examples of MESA Fab Resources



MESA Microfabrication Facility

- Facility specifications
  - 180 tools
  - 89,000 sq. ft. three level structure
  - 16,640 sq. ft. Class 10 and Class 100 clean room space

Of Particular Relevance for Nanoengineering:

- Nanoscale Materials Processing and Characterization (e-beam lithography, CL)
- Materials/Device Integration, including 3D Integration, MEMs
- Capabilities from Materials to Packaged Device Architectures

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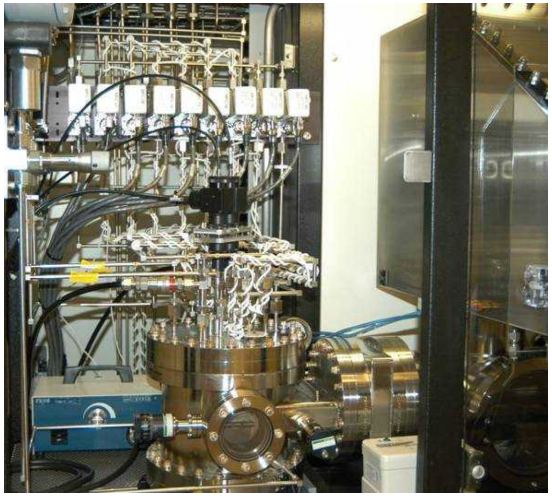
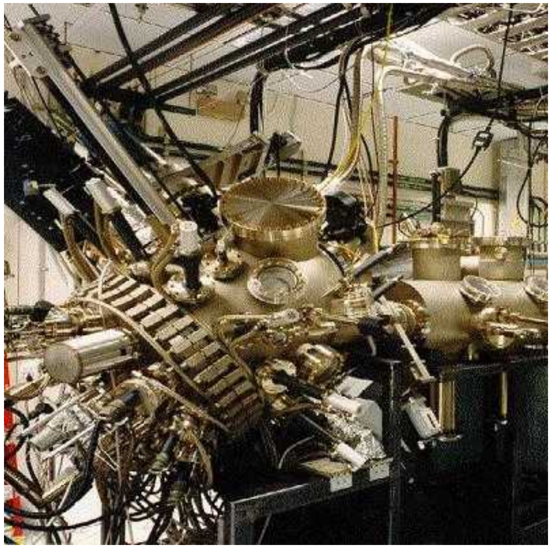
Examples of MESA Fab Resources





State-of-the Art Epitaxial Materials Growth

- **Metal-Organic Chemical Vapor Deposition (MOCVD) reactors (6)**
  - Commercial and experimental systems for the growth of arsenide, phosphide, antimonide and nitride compound semiconductors
  - All have advanced in situ monitoring capability
- **Molecular Beam Epitaxy (MBE) (3)**
  - EPI-B: As, P, Sb and dilute N materials
  - Gen II: As and Sb materials
  - Gen 200 Production Reactor: As, P, Sb and dilute N materials

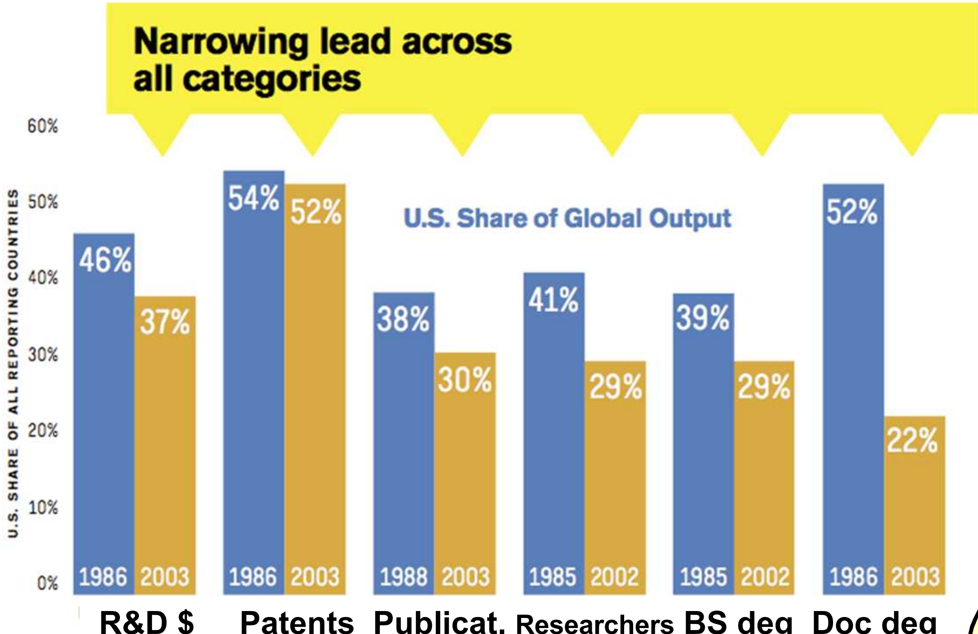
Sandia National Laboratories

NINE is a Nationwide Network of Government/University/Industry Partners …

Regan Stinnett
Sandia National Labs
Albuquerque, NM USA
(rwstinn@sandia.gov)

… who are joining together to support innovation and education in Nano-Engineering through collaborative R&D in key areas

Important trends have increased the urgency for a new approach to maintain U.S. competitiveness



Foreign government, university, industry partnerships are addressing strategic technical areas

Industrial research labs no longer carry the innovation burden for the U.S.

hp invent
Bell Laboratories
EXXON
GE
DUPONT The miracles of science
IBM
GM

The American COMPETES Act outlines a new approach:

Partnerships – Government / University / Industry

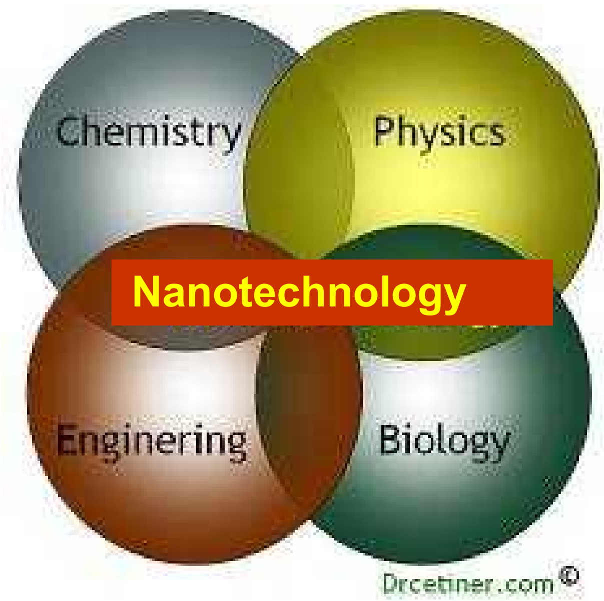
- Invest in research & development
- Strengthen education
- Improve the innovation environment

DOE, with 25,000 researchers & exceptional facilities can help change the game with Innovation Institutes

Sandia National Laboratories

Prototyping the Innovation Institute Concept: *The National Institute for Nano-Engineering*

- **Universities - Industry - National Labs**
- **Supporting Pre-competitive Multi-Disciplinary Projects**
- **Designed For Student Opportunities**



NINE Technology Theme Areas:
- Nanoelectronics & Quantum Info. Proc.
- Nanomaterials Synthesis/Manufacture
- Nanotechnologies for Energy

Sandia National Laboratories

Currently funded Projects in NINE

➢ Nanoelectronics and Quantum Information Processing

- ✓ Nano-electronics and photonics for the 21st Century
- ✓ Atom Chip Device Engineering for Cold Atom Quantum Information Science and Technology
- ✓ Self-assembly to direct manipulation of nanostructures on length scales from atoms to microns

➢ Nanomaterials Processing & Manufacturing

- ✓ Nanocomposite Materials Design: Understanding & Control of Rheology, Assembly, Functionality
- ✓ Phase Imprint Lithography for Large Area 3D Nanostructures
- ✓ Nano-Engineering by Optically Directed Self Assembly
- ✓ Stress-Induced Chemical Detection Using Flexible Nanoporous Metal Organic Frameworks
- ✓ Electrostatic Microvalves Conductive Nanoparticles for Speed, Lower Power, and Higher Force A
- ✓ Interfacial Property Control of Elastomeric Nanocomposites

➢ Nano-based Energy Technologies

- ✓ Nanoengineering for Solid State Lighting
- ✓ Developing a Thermal Microscopy Platform for In-Situ Thermal/Thermoelectric Structure-Property Studies of Individual Nanotubes and Nanowires
- ✓ CO2 Reduction Using Biomimetic Photocatalytic Nanodevices
- ✓ Improving Electronic Structure Calculations to predict Nanocatalyst Functions
- ✓ Optimized Nanoporous Materials
- ✓ Fundamentals of Synthetic Conversion of CO_2 to Simple Hydrocarbon Fuels

Nanoengineering for Solid State Lighting

Objective: to achieve significant energy efficiency advances in Solid State Lighting (SSL) through application of nanoengineering and nanoscience to InGaN-based semiconductor materials and LEDs

Strategic Partner: Rensselaer Polytechnic Institute including the groups of Professor Fred Schubert, Professor Christian Wetzel and Professor Shawn Lin

Description of Effort: Two subtasks address major technical challenges to achieving energy efficient LEDs across the visible spectrum

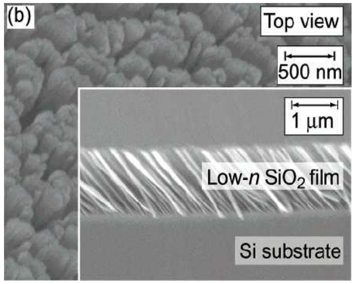
(1) Nanoscale engineering to enhance light extraction of LED materials and devices

- → **novel nanostructured graded index materials**
- → **advanced light extraction strategies (e.g. photonic lattice and surface plasmon approaches)**

(2) Nanoscience studies of InGaN to improve internal quantum efficiency (IQE)

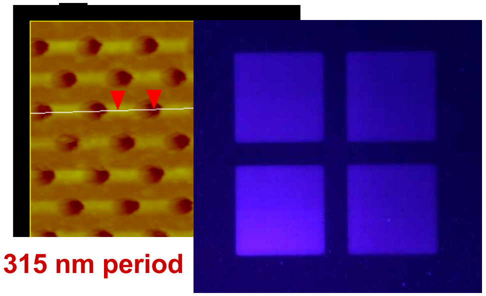
- → **study and control of nanoscale InGaN materials properties that impact luminescence processes**
- → **focus on critical challenges of low efficiency green materials and "efficiency droop" at high currents**

Novel graded index films based on dielectric nanorods



Low index dielectric nanorod arrays through oblique angle deposition

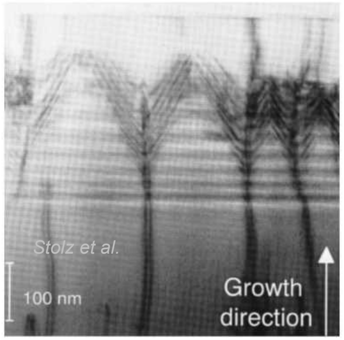
Photonic lattices for light extraction



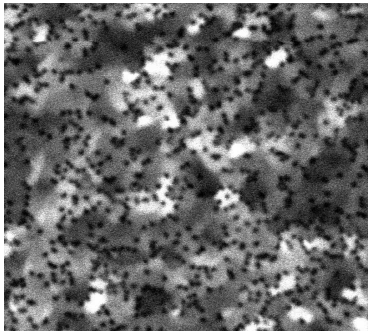
315 nm period

Light extraction from 2 x 2 lattice array

Investigation of nanoengineering of "V-defects" on threading dislocations for enhanced IQE of InGaN



TEM image of V-defects in InGaN multi-quantum wells



Top view cathodoluminescence image of InGaN QWs with V-defects

Sandia National Laboratories

NINE 2008 Summer Program

NINE 2007 summer program

15 projects, 40 students

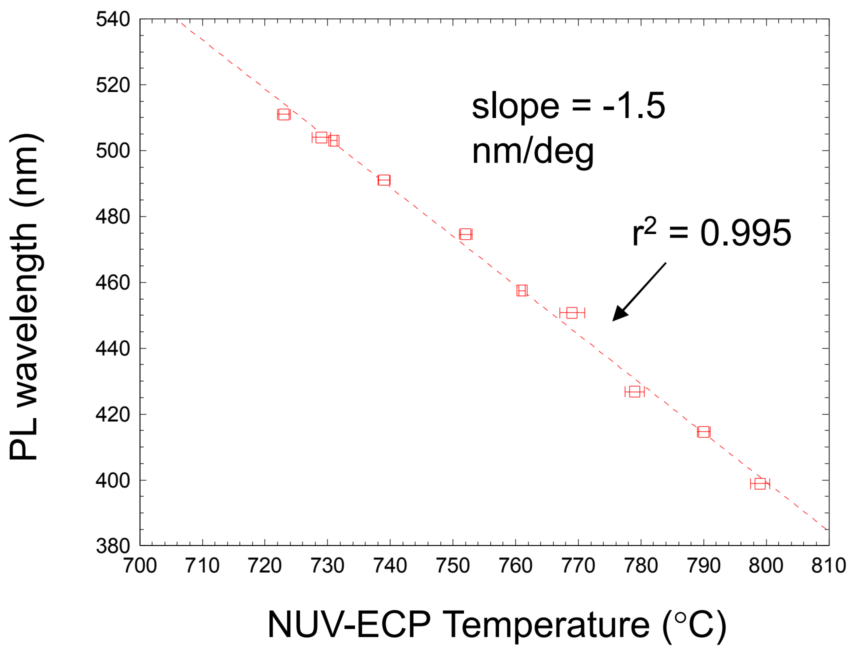
- Students working on NINE projects come to Sandia for 4-9 weeks to work with Sandia mentors and/or industry researchers.
- Presentations and lunch time courses in technology, business, intellectual property, communications for the NINE students.
- Nano-Engineering Expo program with tours, courses, and hands-on nanotech activities for teachers and students.
- NINE industry interns spend 6-10 weeks at industry member’s sites, travel to Sandia for NINE Community Week.
- NINE Community Week July 27-Aug 1. Nano-Engineering Expo Programs for students. Presentations by students. Nano-fest.

Sandia National Laboratories

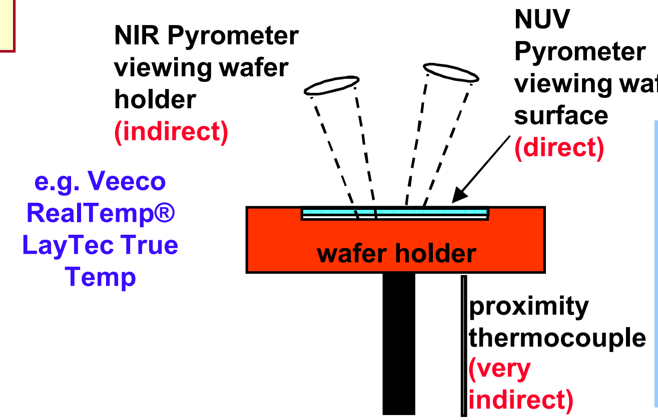
Improved InGaN Epitaxy Yield by Precise Temperature Measurement

Goal: Develop a pyrometer that measures the "true" surface temperature for improved growth control of InGaN alloys

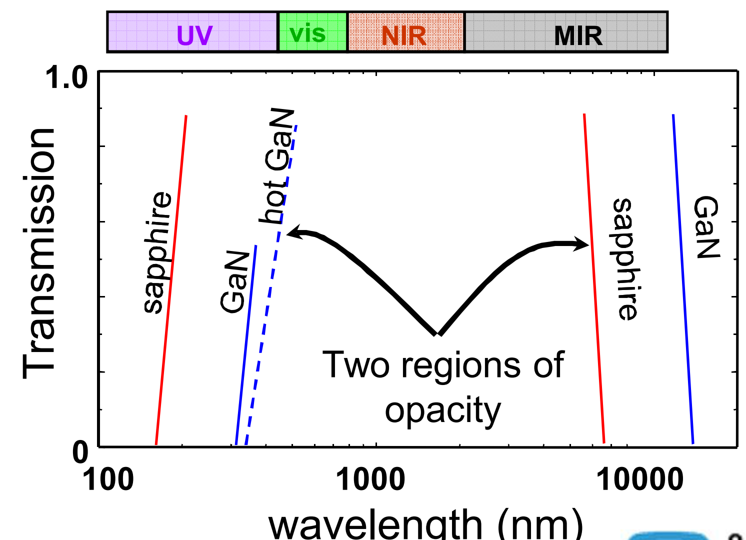
Background: There is a strong temperature dependence on indium incorporation, impacting wavelength control of LEDs in a production process



Various methods of temperature measurement are used with different levels of success.



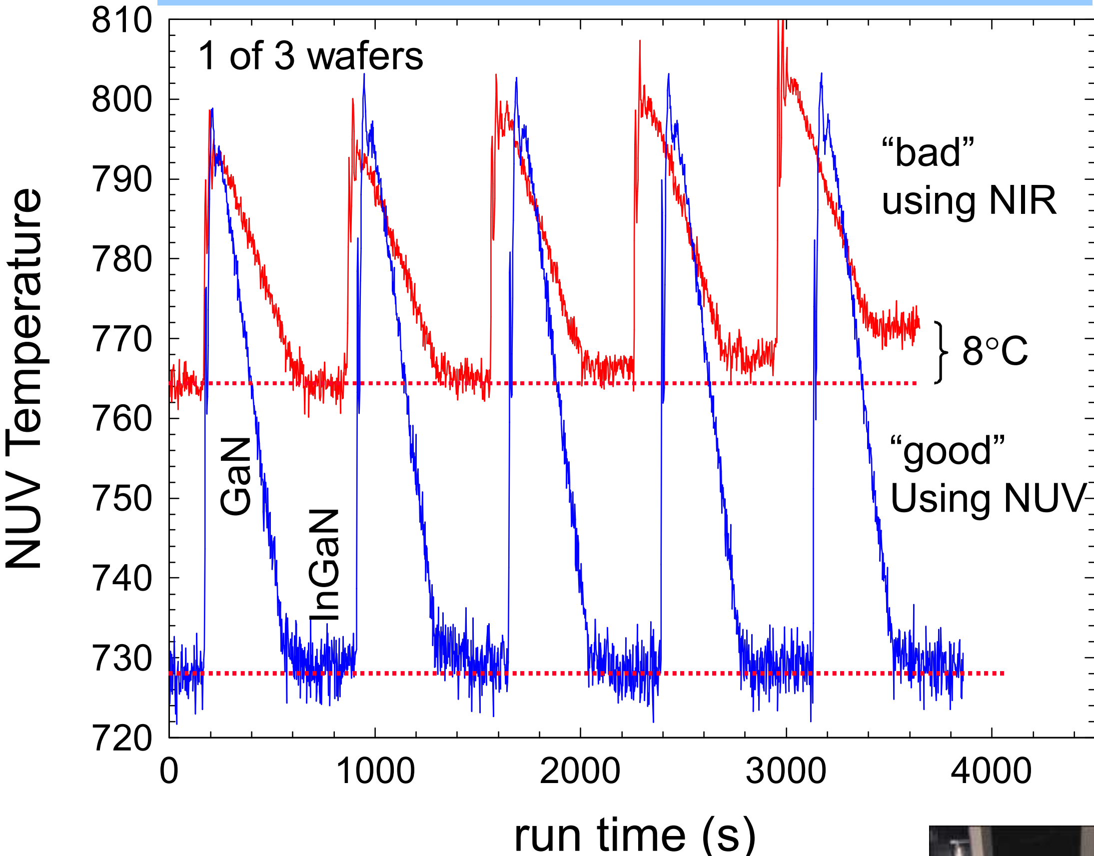
Key: Design pyrometer at wavelengths where GaN is opaque at growth temperature



PI: Randy Creighton

Improved InGaN Epitaxy Yield by Precise Temperature Measurement

Optical Pyrometry Data with NIR and NUV systems

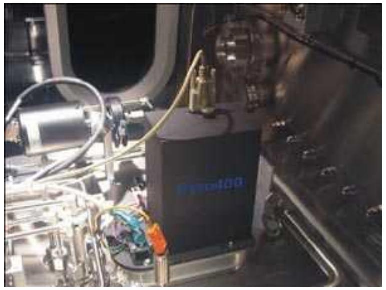


NETL funded research at Sandia

Commercial product

NUV pyrometer developed at Sandia by Randy Creighton, JCG 287, 572 (2006).

In 2007, Laytec developed a commercial UV pyrometer based on research at Sandia.



FEATURE compoundsemiconductor.net

May 3, 2007

UV tool maps nitride temperatures

LayTec is targeting GaN chip developers with an in situ pyrometer that can measure wafer temperatures with a precision of ±0.1 °C. Richard Stevenson investigates.

Profitable chip making demands low development costs and high production yields. To cut expense, growth recipes should be established using minimal runs, because this optimization process can consume a large proportion of the development budget. To do this, process engineers must know as much as possible about the reactor's local environment, including wafer temperature - a primary driver of epilayer growth rates and compositions.

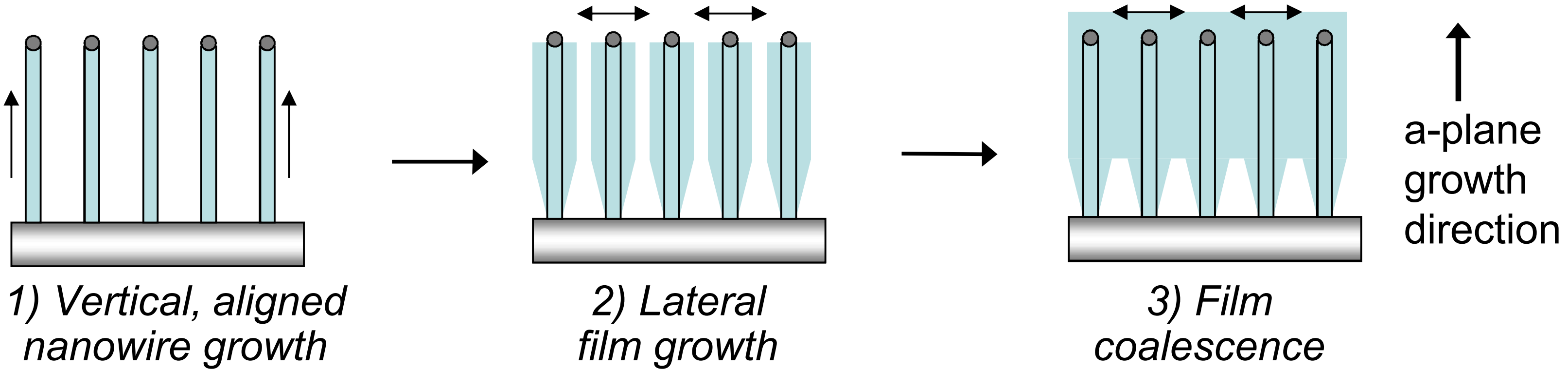
Pyro 400

Pyrometry is the standard method for measuring the wafer's temperatures within a reactor. The technique involves measuring the intensity of thermal radiation emitted by the wafers over a narrow wavelength band using a photodetector, and then correlating this intensity to a temperature. The temperature of wafers based on InP and GaAs material systems can be measured with a pyrometer operating at 950□nm. However, this spectral region is useless for nitrides, because they do not produce any radiation at this wavelength.

To address this deficiency, pyrometers that operate at 400 nm have been built for nitride growth. The first of these was constructed by J□Randall Creighton and co-workers from Sandia National Laboratories, NM, and last year *in situ* monitoring specialist LayTec introduced a commercial version of this tool, the Pyro 400, at the MRS fall meeting in Boston, MA. This instrument is primarily designed for Aixtron multi-wafer reactors, but could be adapted for Thomas Swan tools.

Sandia National Laboratories

Nanowire Templated Lateral Epitaxial Growth of Low Dislocation Density GaN



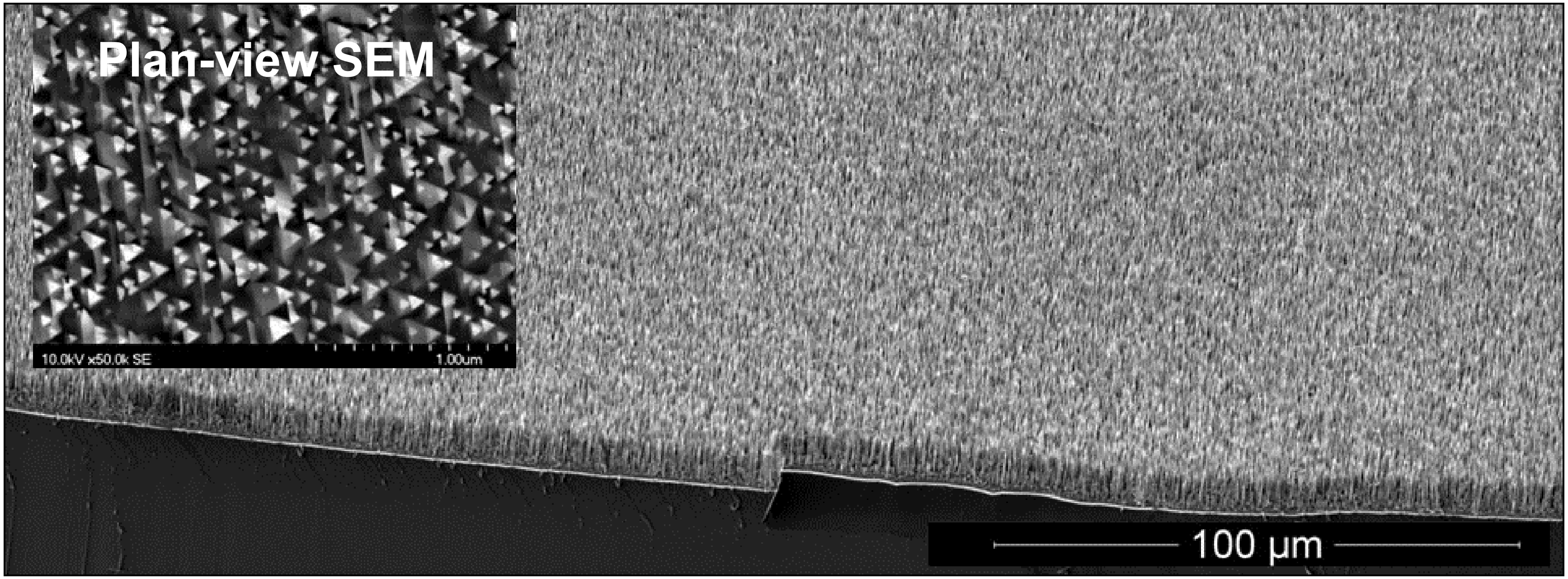
<u>Goal:</u> To develop a novel, low-cost technique employing vertically aligned GaN nanowire arrays for reduced dislocation density GaN.

Advantages of NTLEG approach

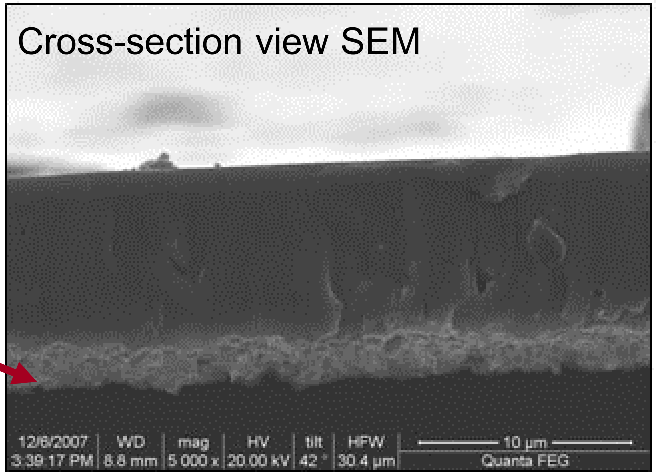
- Dislocation-free nanowire arrays serve as growth template
- **Nanowires serve as 3D-compliant nanoscale bridges connecting film and substrate, relieving strain in the film & reducing defects (nanoheteroepitaxy)**
- Low cost
  - Sapphire can be used (potentially even Si)
  - Requires *no patterning or interruption of growth*
  - Cost is comparable to standard GaN growth on sapphire
- Film takes on nanowire orientation (**non-polar orientations available**)

PI: George Wang

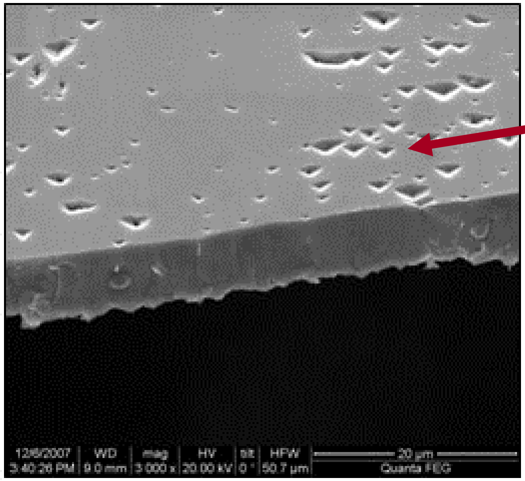
Dense, uniform, vertically aligned growth of GaN nanowires on sapphire over 2” wafer



Fully coalesced *a*-plane NTLEG GaN films demonstrated from nanowire templates



Nanowire ‘legs’

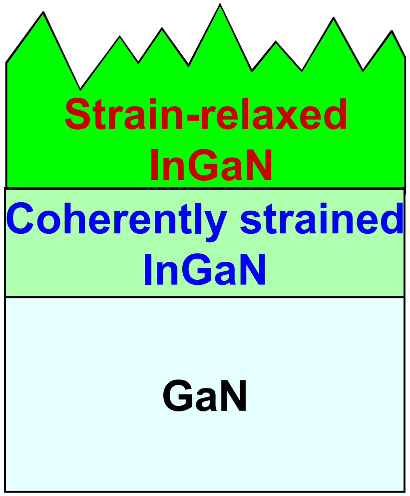


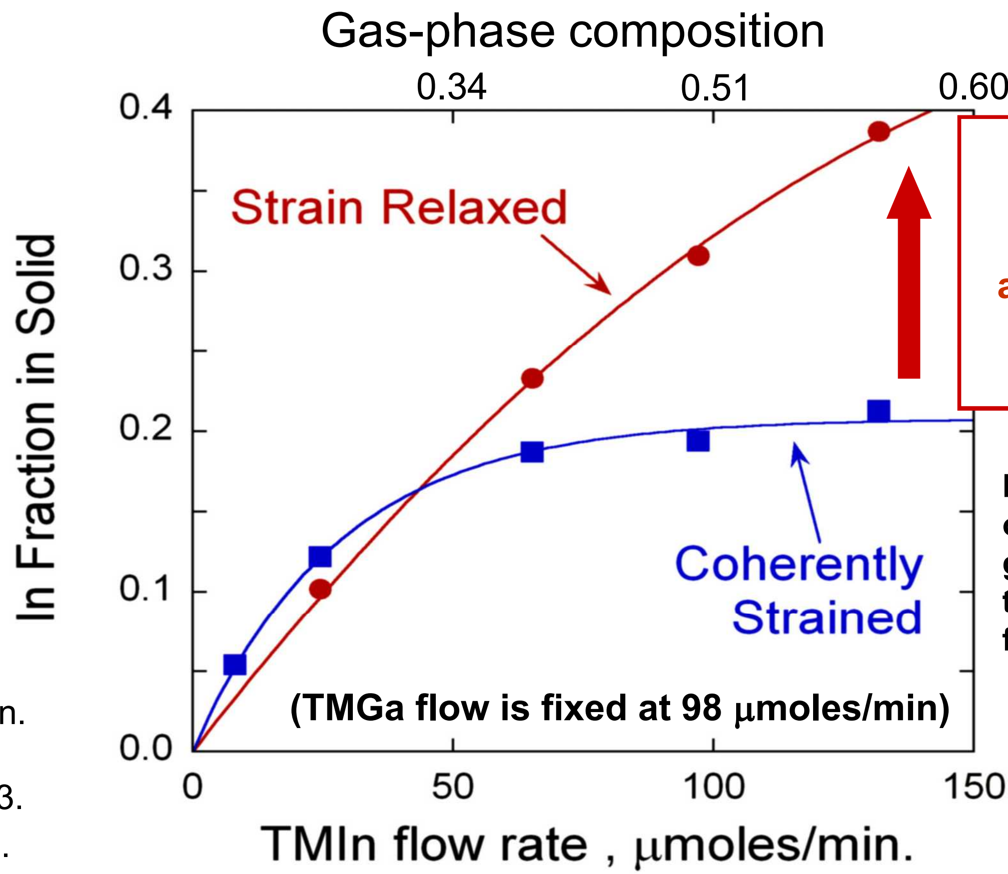
“Free-standing” NTLEG GaN film (nanowires facilitate film removal from substrate)

Sandia National Laboratories

Innovative Strain Engineered InGaN Materials for High Efficiency Green Light Emission

~100-nm-thick InGaN on GaN at 760 C:





For these flow conditions the composition almost doubles upon strain relaxation

Both layers obtained in same growth run using the same MO flow rates

Related observations:

Z. Liliental-Weber, et al., J. Electron. Mat. **30** ('01) 439.

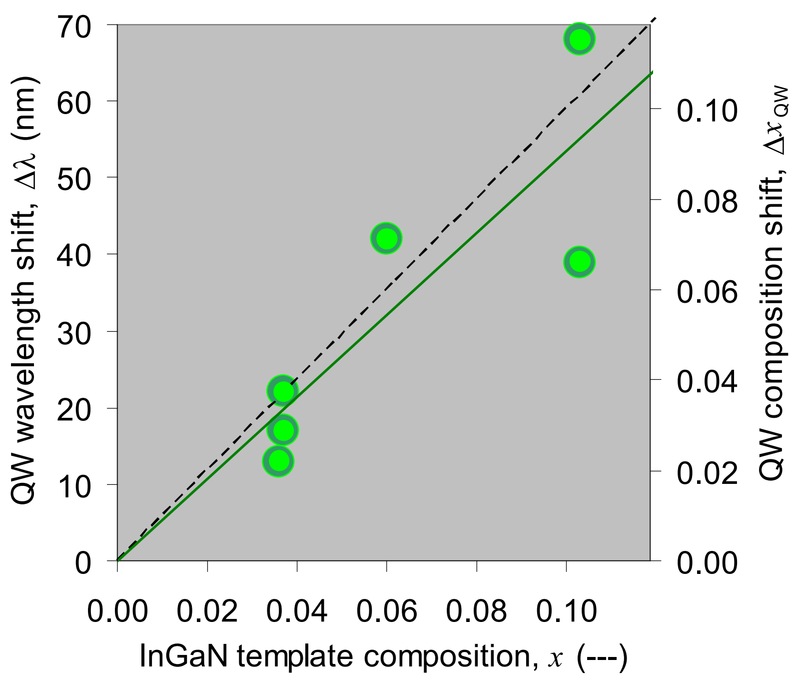
S. Pereira, et al., APL **80** ('02) 3913.

Shimizu, et al., JJAP **36** ('97) 3381.

Need to develop strain relaxed InGaN layers for indium content > 0.2

PI's: Steve Lee, Mike Coltrin

Innovative Strain Engineered InGaN Materials for High Efficiency Green Light Emission



growth run #	GaN template, l_{QW} (nm)	InGaN template, l_{QW} (nm)	Dl_{QW} (nm)	InGaN template, x (---)	InGaN QWs, Dx_{QW} (---)
dnz01166	431	444	13	0.036	0.022
dnz01254	---	479	42	0.060	0.071
dnz01299	442	466	22	0.037	0.037
dnz01376	463	531	68	0.103	0.115
dnz01439	429	446	17	0.037	0.029
dnz01439	429	468	39	0.103	0.066

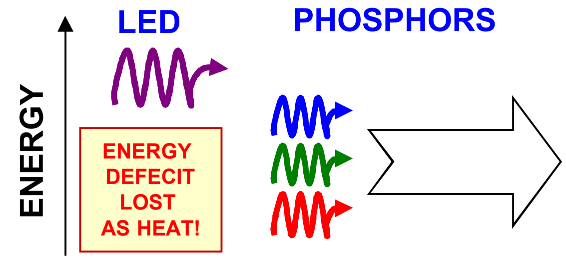
- **QW compositions on standard GaN templates were x_{QW}~0.13-0.16**
- **Compositions of similarly grown QWs on relaxed $In_{0.10}Ga_{0.90}N$ approach x_{QW}~0.26**

Increase in InGaN QW composition is directly proportional to the composition of the relaxed InGaN template

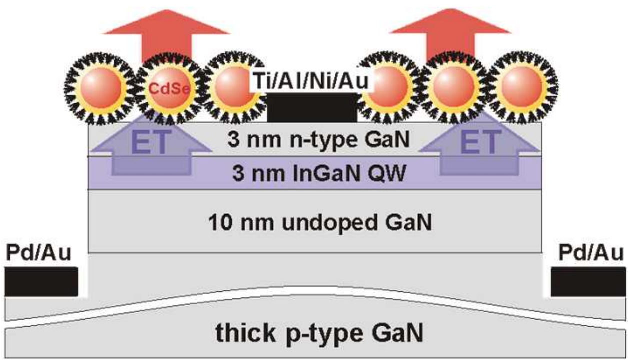
Energy Transfer (ET) from a Quantum Well to Nanoclusters

Energy Efficiency is Crucial for SSL!

How to avoid significant energy loss when exciting phosphors or nanoclusters with UV photons?



Exciton injection through energy transfer: Förster type dipole-dipole interaction

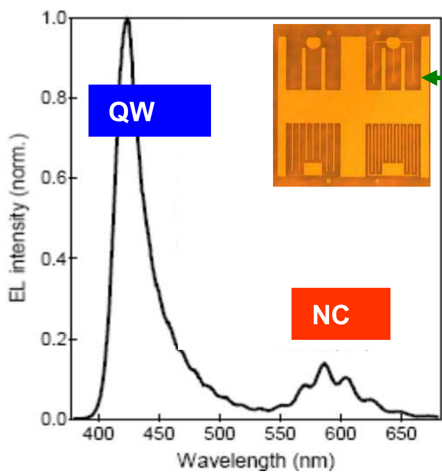


ET theory for unbound e-h pairs in the QW

$$\Gamma_{ET} = \frac{8\pi^2}{3\varepsilon^2}\left|\mu_{NC}\right|^2\left|\mu_{QW}\right|^2 n_{NC} n_{eh} N_{NC}(\hbar\omega_{QW})\frac{1}{d^4}\frac{\hbar^2}{2Mk_BT}\int_0^\infty \kappa^3 \exp\left(-2\kappa - \frac{\hbar^2\kappa^2}{2Mk_BTd^2}\right)d\kappa$$

Linear in QW e-h pairs

Strong distance dependence



InGaN "n-on-p" LEDs with interdigitated contacts

Reported in: M. Achermann, M.A. Petruska, D.D. Koleske, M. Crawford, V.I. Klimov, *Nano Letters* (2006)

- Electrical injection to excite InGaN QW
- Energy transfer to NCs by dipole-dipole interaction
- $1/d^4$ dependence makes implementation in p-n junction devices *very challenging* (~ few nm QW-NC separation)

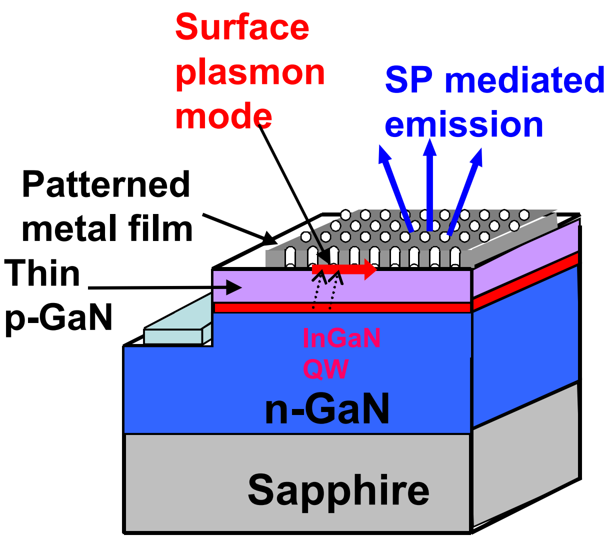
LANL / SNL Development of Electrically injected ET-LED Structure

Initial results >10% NC emission! (I_{NC}/I_{QW})

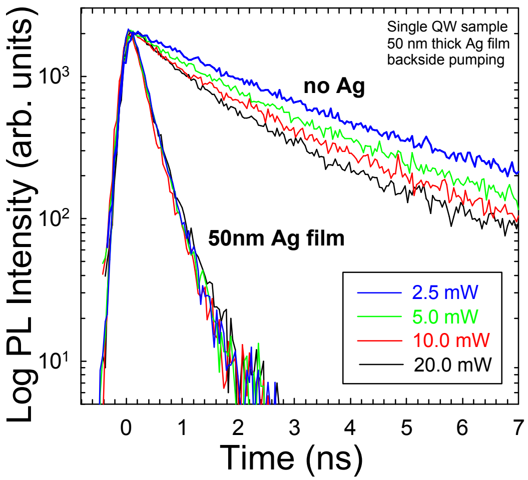
SNL: Dan Koleske, Mary Crawford

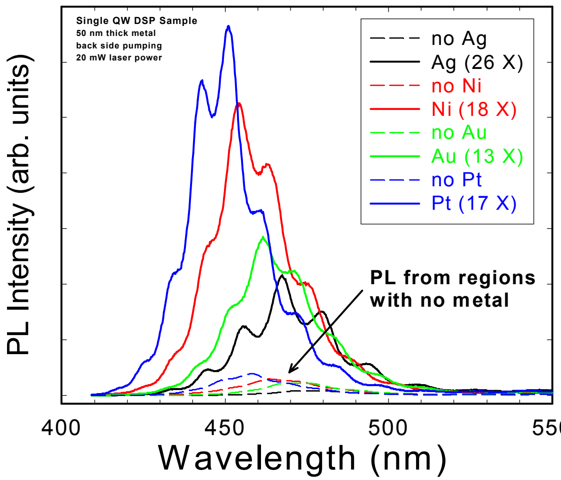
Surface Plasmon Light Emitting Diodes

InGaN Surface Plasmon LED

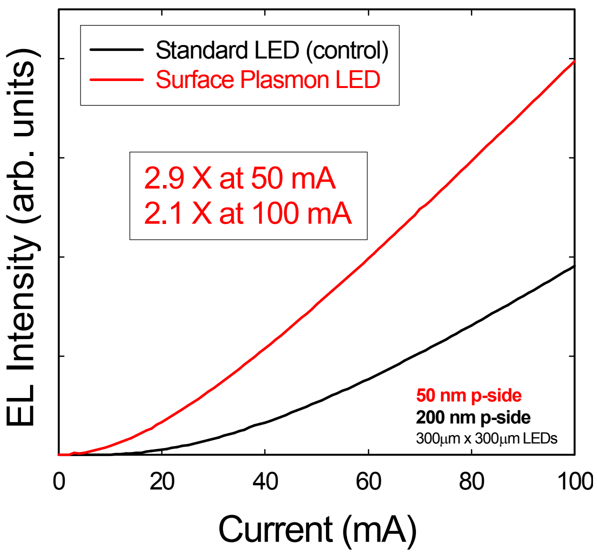


PL measurements





LED L-I measurements



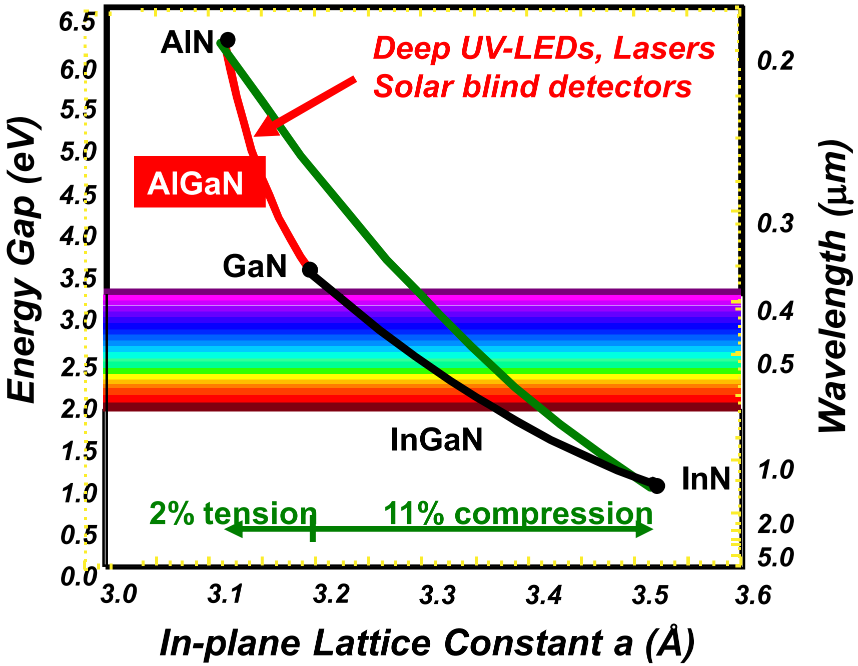
LED output is enhanced by 2 to 3 times with thin p-side surface plasmon LED designs

Advantages of Design:
- Improved IQE (green LEDs)
  - rapid coupling from QW to SP
- Same design improves IQE and extraction
- Enhanced IQE using existing materials

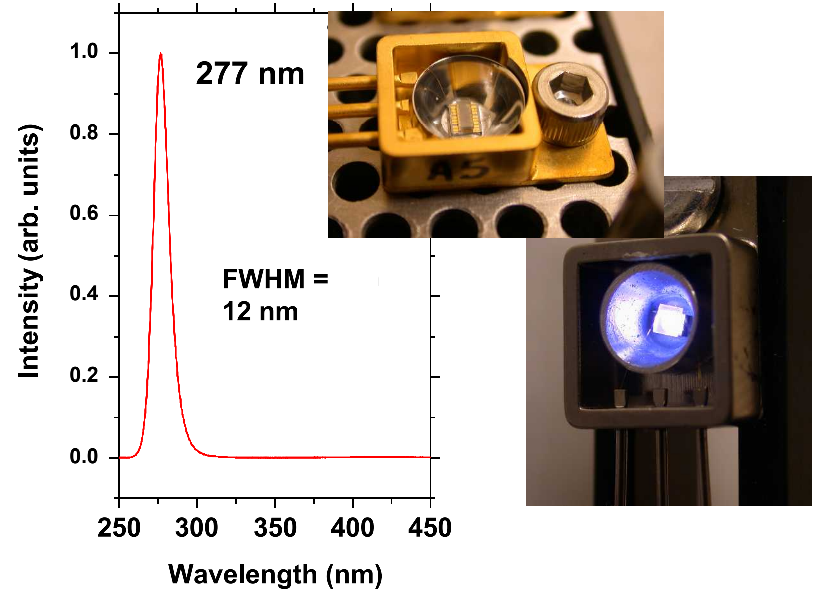
Primary Challenges:
- QW placement near surface
- Design of patterned metal film

PI: Art Fischer

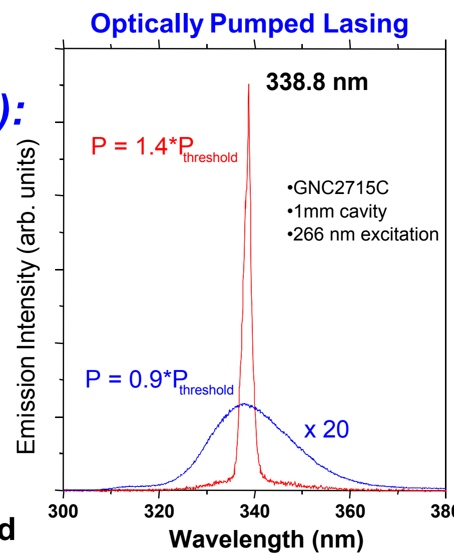
Deep Ultraviolet LEDs and Lasers

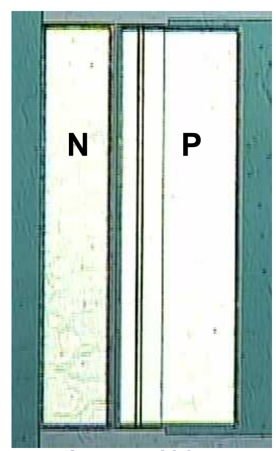


> 2 mW output at 275-300 nm from AlGaN LEDs (1 mm x 1mm devices), 237 nm LEDs

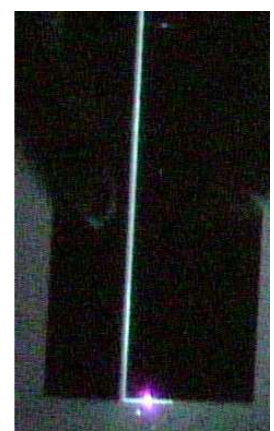


340 nm Laser Diode Development (on-going):





4 µm x 400 µm RWG test structure


Device under test (CW)

PIs: Andy Allerman, Mary Crawford

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